TD-99-033

HGQ-06 Fabrication Report

Kerby, Zlobin, Nobrega, Bossert, Chichili, Novitski, Arkan, Ozelis, Yadav, Andreev

1.0 Introduction

Magnet HGQ06 was similar to HGQ05 with the most notable differences being the QI cable insulation which requires a higher cure temperature of 190 C, the iteration of the end design to 5 blocks from 4 and the use of G-11 end part material. All the changes from magnet 5 to 6 are listed below in Table 1.1 and are highlighted in red and italicized.

Inner Cable Strand No.	38
Inner Cable lay direction	***Left Lay***
Outer Cable Strand No.	46
Outer Cable lay direction	Left Lay
Cable Pre-baking	None
Strand Coating	None
Cable Cleaning	Axarel 6100
Inner Cable Insulation	***25uM x 9.5mm w/ 55% overlap surrounded by 50uM x 9.5mm w/2mm gaps w/QI***
Outer Cable Insulation	***25uM x 9.5mm w/ 50% overlap surrounded by 25uM x 9.5mm w/41% overlap w/QI***
Coil Curing temperature	190C
Inner Coil target size	***+.007 in., +175uM***
Inner Coil MOE	***9.5GPa***
Outer Coil target size	***+.007 in., +175uM***
Outer Coil MOE	***9.5GPa***
Target Prestress	65-70MPa
Coil end azimuthal Shim System	Shim ends to be same as body, tapering off toward end of saddle.
End Part Material	***G-11***
End Part Configuration	***Iteration #2, 5 block design.***
Splice Configuration	Internal
Voltage Tap Plan	MD-369212/MD-369213
Inter layer strip heaters	***None***
Outer layer strip heaters	***SSC Design, single element***
Key extension	None

Inner coil Bearing Strips	Brass, cut in 3 inch segments, same as collar packs.
Outer coil Bearing Strips	Phosphor bronze, cut in 3 inch segments, same as collar packs.
Collar configuration	3 inch long "solid" welded packs, with 49 lamination period.
Collar key configuration	3 inch long, positioned same as packs.
Strain Gauges	4 beam gauges on outer coil, 4 capacitor gauges on inner coil, 4 capacitor gauges on outer coil.
Spot Heaters	Pole turn on 2 outer coils, at lead end on parting plane turn on 1 outer coil.
End Radial Support	***Collet end clamps on both ends. Aluminum exterior cans with G-11 quadrant pieces.***
Collar/Yoke Interface	Radial clearance between collar and yoke.
Quadrant Lead Configuration	***Double lead with copper only cable for stabilizer***
End longitudinal loading	Bullets apply load directly to coils, 2000 lbs. force per bullet. End cans are bolted to end plates longitudinally, preventing coils from contracting longitudinally.
Yoke Key Width	24mm
Strain Gauges on Skin	Yes
End Plate Thickness	50mm
Tuning Shims	***None***
Other	Return end keys mold released and replaced. 2 collar packs with thermometers.

Coil Fabrication Start Date	2/25/99
Collared Coil Start Date	4/5/99
Yoke Assy Start Date	5/14/99
Completion Date	6/10/99

Table 1.1 HGQ06 features.

2.0 Superconducting Cables

2.1 Mechanical Parameters

Table 1 summarizes the cable parameters used in HGQ-06. Note that the pitch direction for the inner cable used in HGQ-06 is a left lay unlike the previous model magnets. While slightly more difficult to wind, no problems occurred with the left lay cable.

PARAMETER	UNIT	INNER CABLE FOR HGQ-06	OUTER CABLE FOR HGQ-06
Radial width, bare	mm	15.40	15.396
Minor edge, bare	mm	1.320	1.051
Major edge, bare	mm	1.610	1.241
Midthickness, bare	mm	1.465	1.146
Keystone angle,	deg	1.110	0.661
Number of strands		38	46
Lay direction		***Left***	Left

Table 2.1.1: *Cable parameters as provided by LBNL.*

The cables were cleaned before insulation with Axarel 6100 in the SSC cleaning module. Even though the cable was dried after cleaning, it was still wet during winding and the Axarel can be seen through the Kapton on the spool.

2.2 Electrical Parameters

Parameter	Unit	Inner Cable	Outer Cable
R(295 K)	μohms/cm	16.38	18.50
R(10 K)	μohms/cm	0.34	0.47
RRR		48.18	39.36
C/Sc		1.23	1.76

Table 2.2.1: *Cable Electrical parameters*

2.3 Cable Test Data

	Inner Cable		Outer Cable	
B,T	Ic ,KA	Jc, A/mm^2	Ic ,KA	Jc, A/mm^2
6	19.31	2,190.29	12.97	2,341.70
7	14.30	1,621.91	9.63	1,738.71
8	9.29	1,053.53	6.29	1,135.72

Table 2.3.1: *Cable test data*

3.0 Coil Fabrication

3.1 Cable and Wedge Insulation

Several R&D coils were wound to determine the insulation overlap percentage for obtaining the right size and modulus for the coils. Table 3.1.1 summarizes the final cable insulation parameters used in HGQ-06. Note that the mold size for the inner coil curing fixture was +2 mils and for the outer coil curing fixture was +5 mils. R& D coils were also wound to determine if we could use Kapton with QIX adhesive instead of QI. After curing at 190 ^{o}C we found epoxy flashing on the inside diameter of the pole and the Kapton was wrinkled / deformed at some areas. This phenomenon was observed even after reducing the curing temperature to 180 ^{o}C. So it was decided that we would stick with QI for HGQ-06 coils.

The wedges were insulated identical to their respective coils. Since the HGQ-06 cable was not baked, the wedges were placed in 3 sections with the gaps in the body of the coil. We however decided to stager the breaks in the wedges such that they do not coincide at the same cross-section.

PARAMETER	**INNER CABLE**	**OUTER CABLE**
Number of wraps	2	2
Inner wrap: -material -adhesive -wrap structure	 Kapton tape 25 μm × 9.5 mm None Spiral wrap with 55% overlap	 Kapton tape 25 μm×9.5 mm None Spiral wrap with 48% overlap
Outer wrap: -material -adhesive -wrap structure	 Kapton tape 50 μm ×9.5 mm Liquid polyimide (QI) Spiral wrap with 2 mm gaps	 Kapton tape 25 μm × 9.5 mm Liquid polyimide (QI) Spiral wrap with 41% overlap

Table 3.1.1: *HGQ-06 cable insulation parameters.*

3.2 Winding and Curing

Five inner and five outer coils were wound, cured and measured for HGQ-06. All coils had wedge breaks staggered such that the breaks would not be coincident at any longitudinal location in the same coil. From the lead end, the wedge lengths were 25”, 22.6” and 19” on one side and 19”, 22.6” and 25” on the other side. The gaps before curing were 0.085”. Outer coil # 041 had a different wedge gap layout from the other coils. Side “A” measured from the lead end had wedge lengths of 13”, 21.5” and 31” and on the “B” side, also measured from the lead end, had wedge lengths of 19”, 21.6” and 25”. The quality of the first inner coil was not as good as HGQ-05 coils. There was no adhesion between the cable and the Kapton placed between the LE key and the 1st turn. Note that the Kapton was placed between the LE key and the cable to reduce the risk of cable to ground shorts as we eliminated the key extensions. Also the adhesion between the first three turns was not good at both the ends. The quality of the subsequent coils were improved by (i) coating the Kapton placed between the LE key and the first turn with b-stage epoxy and (ii) placing the QIX sheet adhesive between the first three turns near the LE and RE. One last change in HGQ-06 inner coils was that the RE key was mold released with Teflon. The idea is to modify the length of the keys before collaring coil assembly to get a co-planar RE. This was necessary for coil length adjustment as we eliminated key extensions. A Kapton layer was also placed between the RE key and the 1st turn during the final assembly.

3.3 Coil Measurements

3.3.1 Coil Straight Section

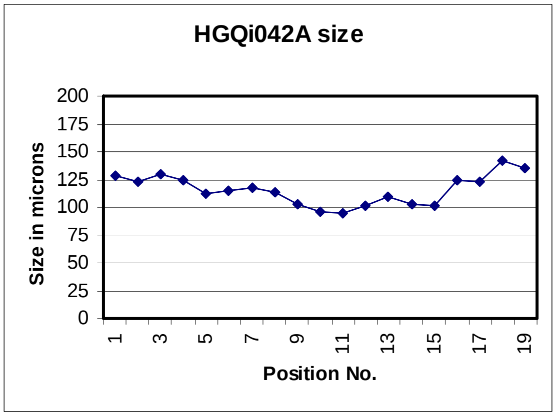
The coil azimuthal size and modulus measurements were taken over a range of pressures, 55 to 100 MPa. The design pressure for both the coils when warm and unpowered is about 65 MPa. Coils were measured with 3 inch gauge length along the straight section of the magnet, from LE to RE. The ends of the magnet were measured separately using end-compression unit and will be discussed in the next section. Table 3.3.1 list the coil numbers and the corresponding average coil size and modulus.

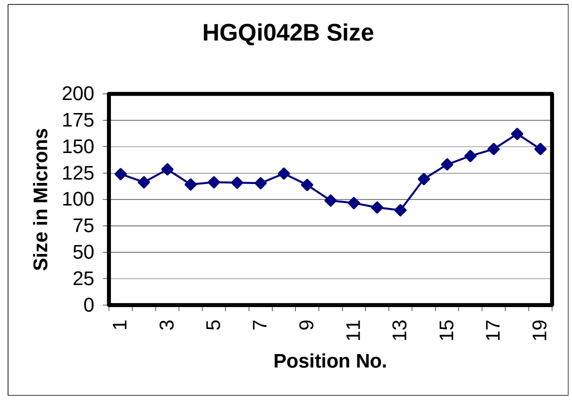
Coil Number	**Size, μm**	**Modulus, GPa**
HGQi-044	141	9.6
HGQi-045	158	8.9
HGQi-046	152	9.4
HGQi-047	144	9.4
HGQo-038	142	9.6
HGQo-039	156	10.1
HGQo-040	162	9.9
HGQo-041	124	8.9

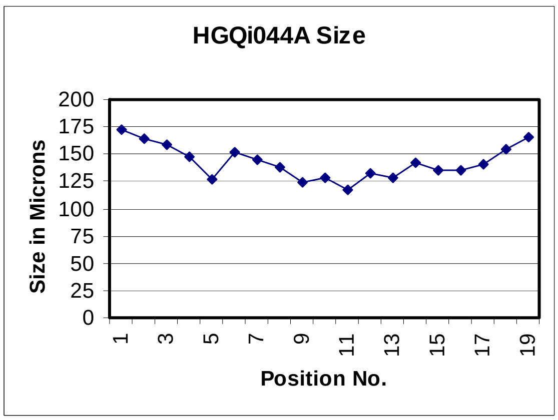
Table 3.3.1: *HGQ-06 coil body size and moduli*.

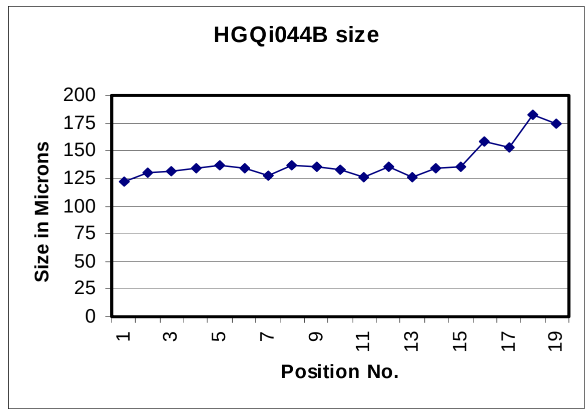
Note that the moduli of both inner and outer coils are very similar. The target size for both inner and outer coils is +175 μm.

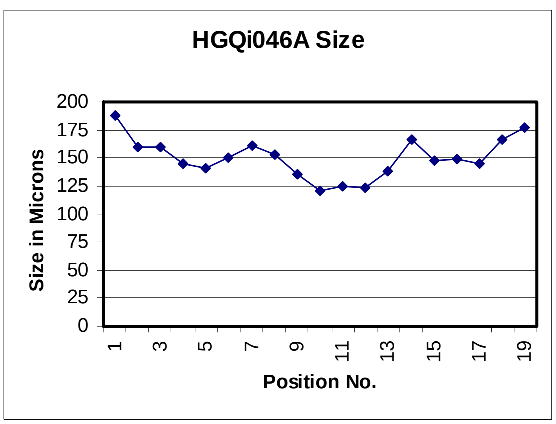
Variation of the size along the length of the coils are shown in Fig 3.3.1. Note that Side A is the winding side of the cable and the lead end of the cable is on Side B.

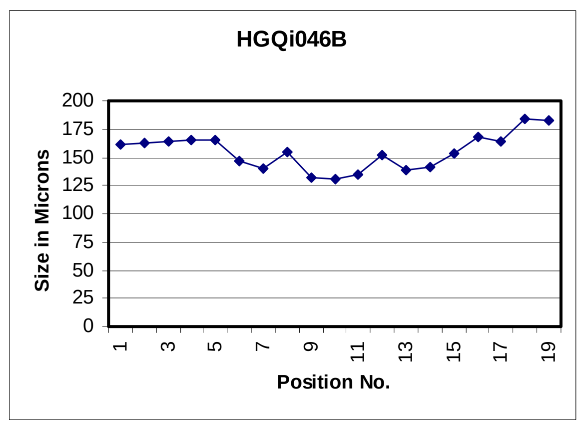

HGQi042A size
Size in microns
Position No.

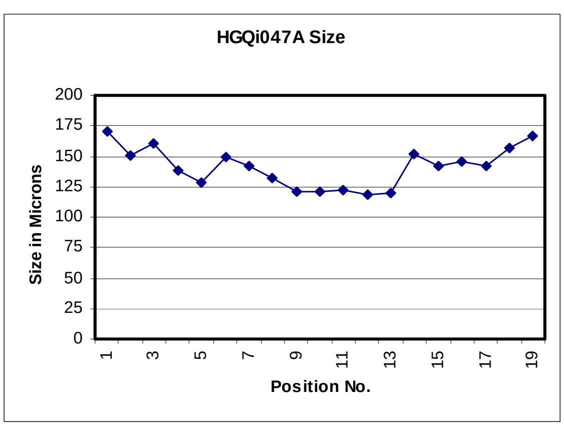

HGQi042B Size
Size in Microns
Position No.

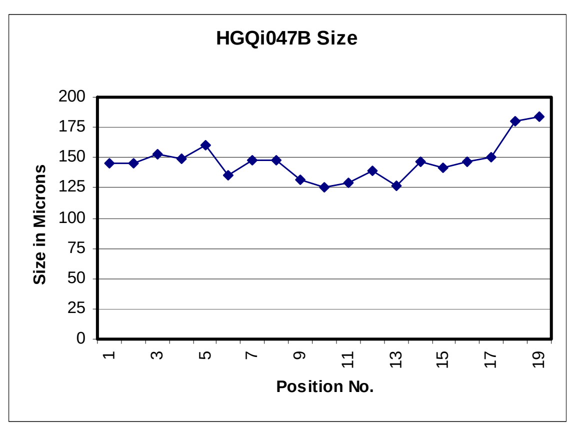

HGQi044A Size
Size in Microns
Position No.


HGQi044B size
Size in Microns
Position No.


HGQi046A Size
Size in Microns
Position No.


HGQi046B
Size in Microns
Position No.


HGQi047A Size
Size in Microns
Position No.


HGQi047B Size
Size in Microns
Position No.

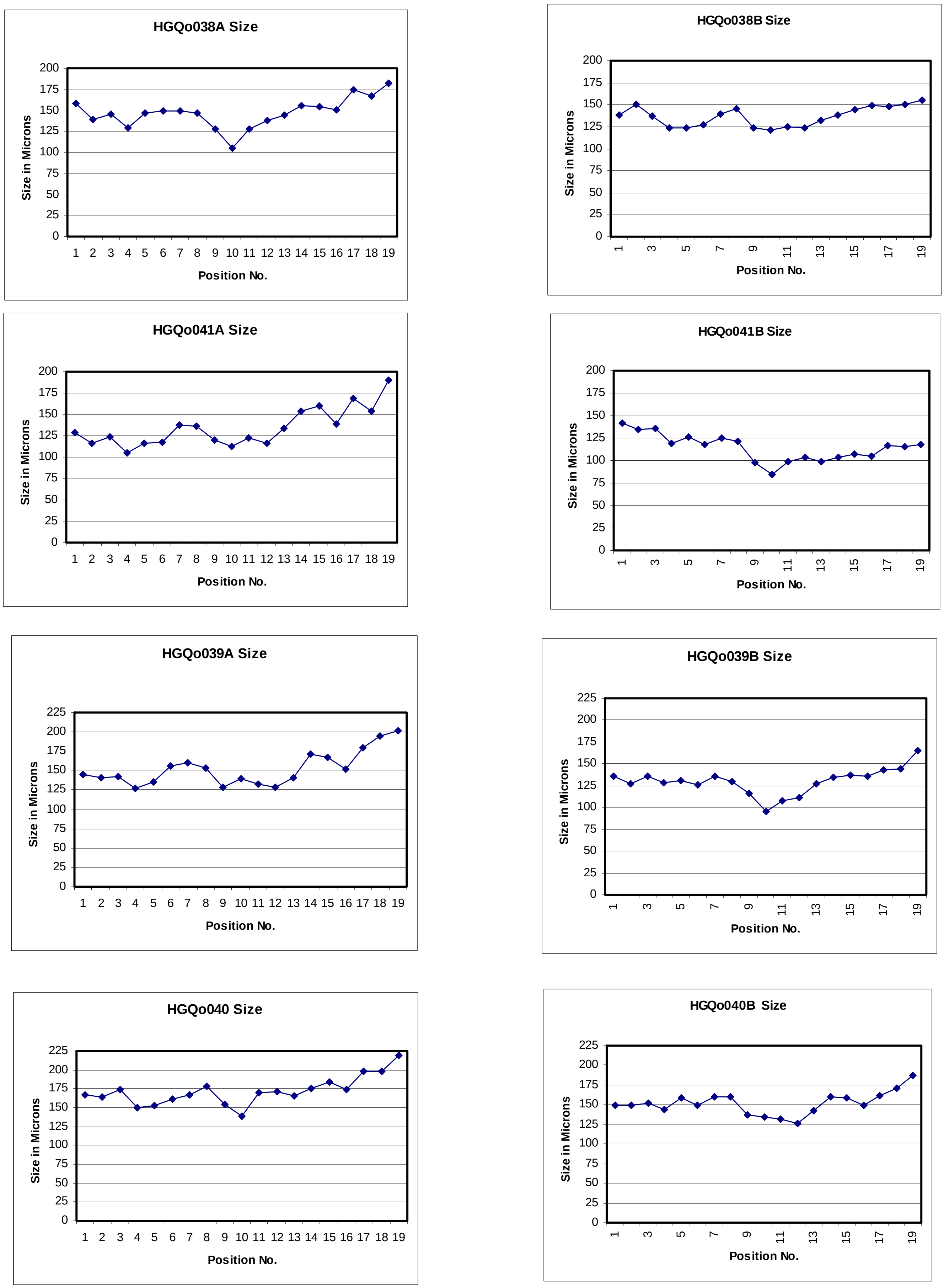


Figure 3.3.1: *Variation of coil size for inner and outer coils along the length of the straight section.*

3.3.2 Coil Ends

End-compression experiments were performed to determine the end-shape and size of the coils. Since this was the first magnet to use G-11 end-parts and also a five block design for inner coils, these experiments were also used to check the differences in end-shape between four block and five block design. Figs. 3.3.2 to 3.3.5 shows the end measurements for both LE and RE of inner and outer coils.

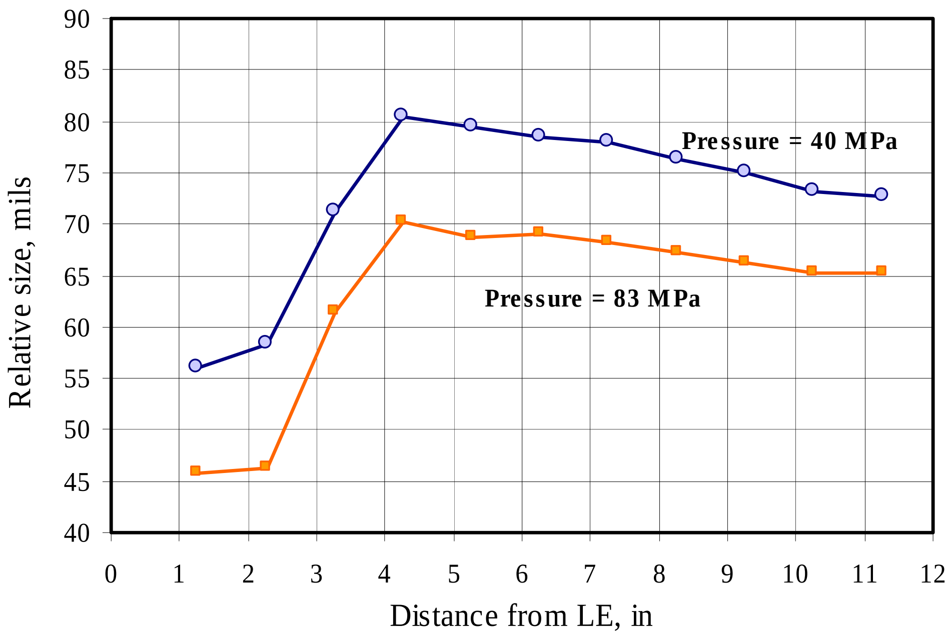


Figure 3.3.2: *End-compression measurements on a inner coil LE.*

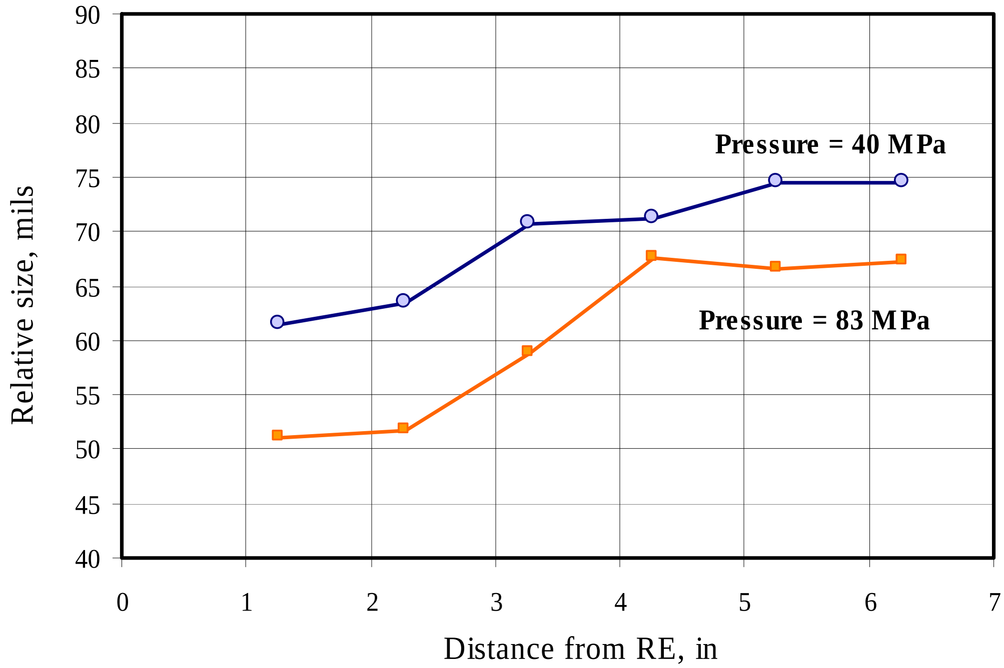


Figure 3.3.3: *End-compression measurements on a inner coil RE.*

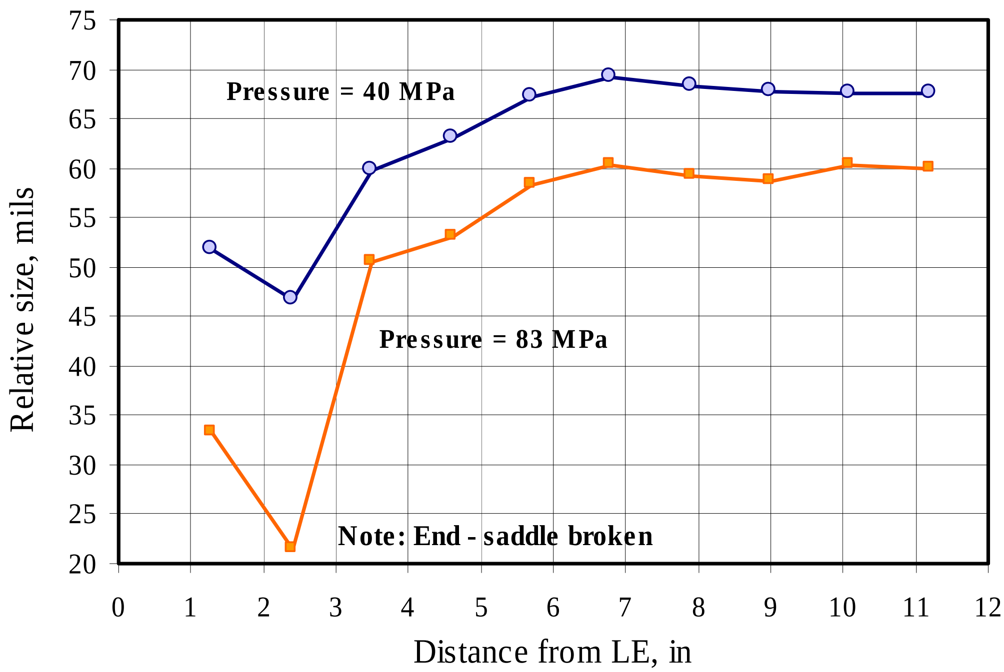


Figure 3.3.4: *End-compression measurements on a outer coil LE.*

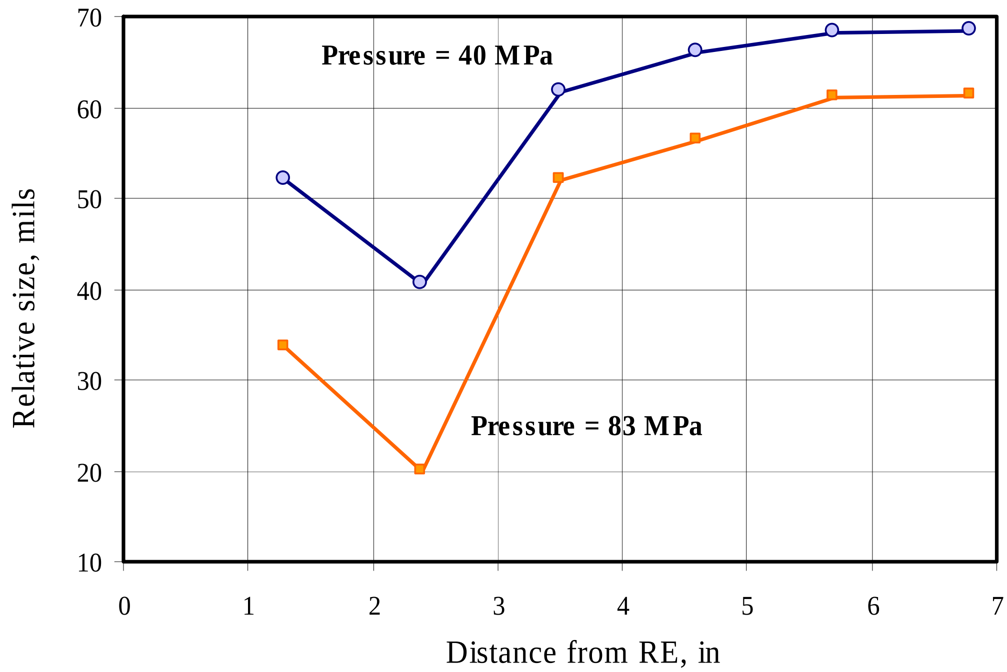


Figure 3.3.5: *End-compression measurements on a outer coil RE.*

3.4 Coil Shimming

3.4.1 Coil Straight Section

The target pre-stress for HGQ-06 is about 65 MPa. This corresponds to a nominal coil size of +175 μm for both inner and outer coils. For the inner coils the size varied from 146.5 to 151.5 μm with an average of 149 μm; whereas the outer coil size varied between 135.5 to 151.5 μm with an average of 142 μm. The inner coils were shimmed up by 25 μm (1 mil) and the outer coils by 50 μm (2 mils) (see Table 3.4.1). The amount of shimming was biased towards the outer coils to achieve higher pre-stress in the outer coils than in inner coils.

I/O	Quadrant	Coil #	Coil Size	Shim Pole	Shim PP	Target	Actual	Mean
Inner	1A	i-044	143	25	0	175	168	
Inner	1B	i-044	139	25	0	175	164	
Inner	2A	i-046	150	25	0	175	175	
Inner	2B	i-046	155	25	0	175	180	
Inner	3A	i-047	141	25	0	175	166	
Inner	3B	i-047	147	25	0	175	172	

Inner	4A	i-045	154	25	0	175	179	
Inner	4B	i-045	162	25	0	175	187	174
Outer	1A	o-040	172	25	25	175	222	
Outer	1B	o-040	151	25	25	175	201	
Outer	2A	o-039	152	25	25	175	202	
Outer	2B	o-039	130	25	25	175	180	
Outer	3A	o-038	147	25	25	175	197	
Outer	3B	o-038	137	25	25	175	187	
Outer	4A	o-041	134	25	25	175	184	
Outer	4B	o-041	114	25	25	175	164	192

Table 3.4.1: *Shimming used in coil straight section (From R. Bossert).*

3.4.2 Coil Ends

The end-shimming was done similar to HGQ-05 without the custom made Kapton pieces at the dip. Figs. 3.4.1 through 3.4.4 shows the shim plan implemented in HGQ-06. Fuji film results showed uniform load distribution in the ends.

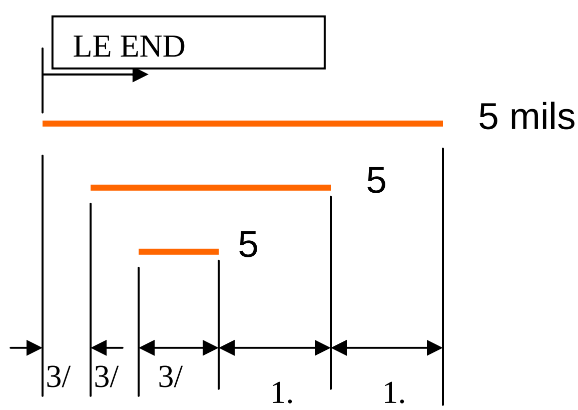


Figure 3.4.1: *End-Shimming for inner coil LE*

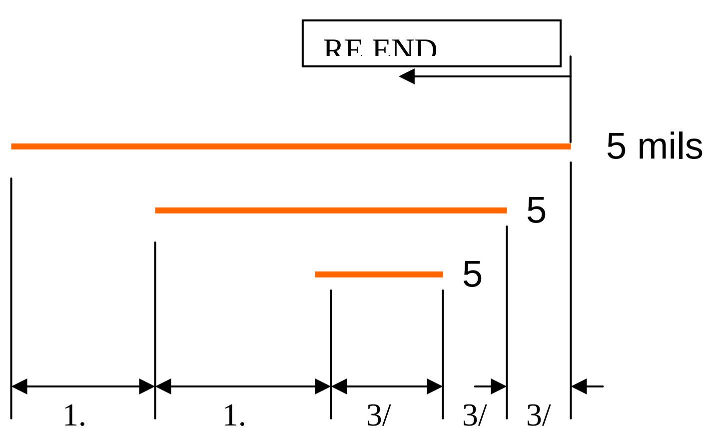


Figure 3.4.2: *End-Shimming for inner coil RE.*

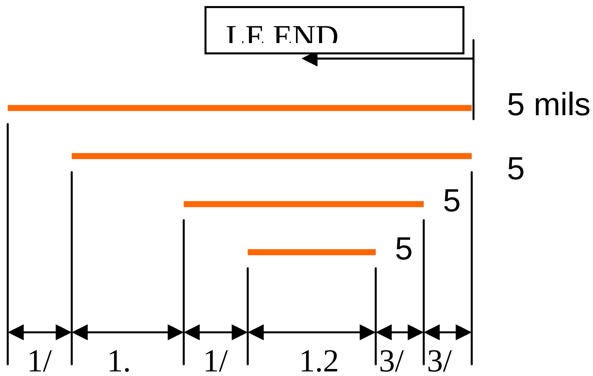


Figure 3.4.3: *End-shimming for outer coil LE.*

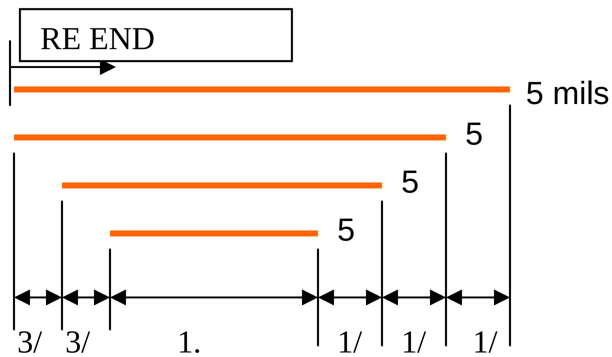


Figure 3.4.4: *End-shimming for outer coil RE.*

3.5 Voltage Taps and Spot Heaters

Voltage taps were mounted according to the drawing number 5520-MD-344972 for inner coils and 5520-MD-344973 for outer coils. End-compression tests with a 5 inch pusher bar were done on all HGQ-06 coils after putting the voltage taps to check for turn-to-turn shorts. None of the coils showed any shorts.

Spot heaters were installed between the end-saddle and the last turn during winding on outer coils HGQo-040 and 41. Spot heaters were also installed between the 16^{th} turn and the G-11 spacer in outer coils, HGQo-038 and 39 later during collared coil assembly.

4. Coil Assembly

4.1 Coil Arrangement

Coils in HGQ magnets are arranged to obtain the most uniform possible preload distribution between quadrants, given the coils available. The coil arrangement is shown in Figure 4.1.1. The amount of shim placed at each pole and parting plane is shown in red (positive numbers indicate kapton added, negative numbers indicate kapton removed). Shims are frequently added to (or removed from) the parting plane and/or pole area to achieve the "target" azimuthal coil size and hence the desired preload. See also section 3.4 for a discussion of coil shimming.

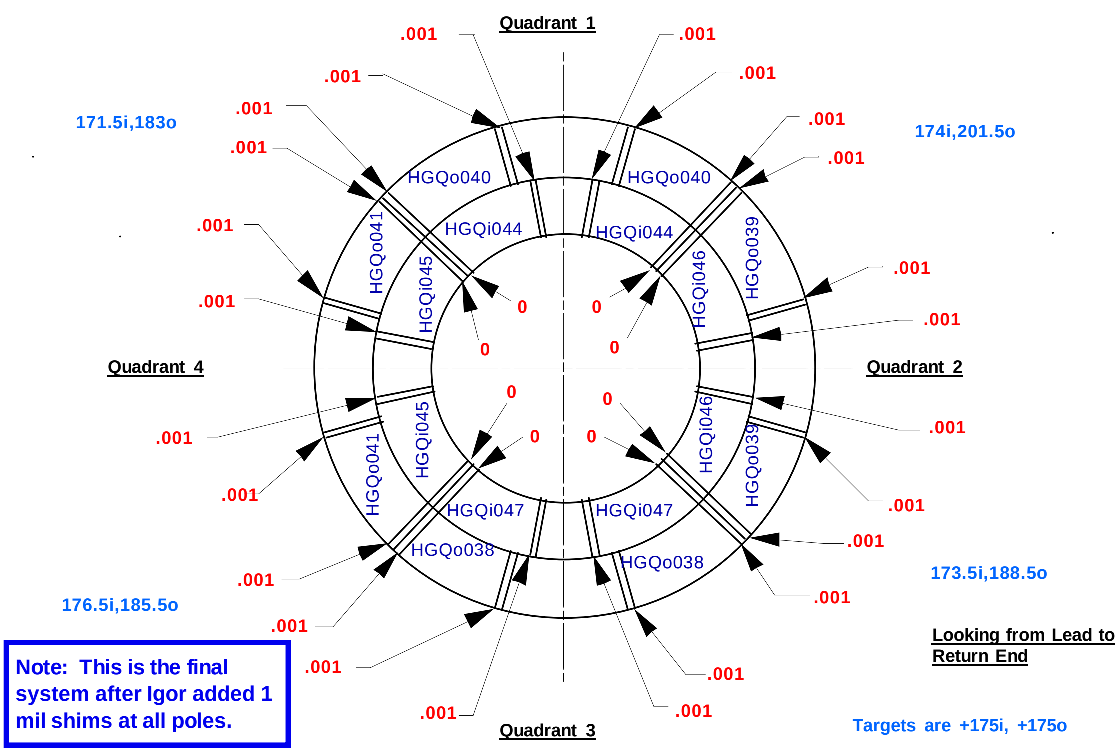
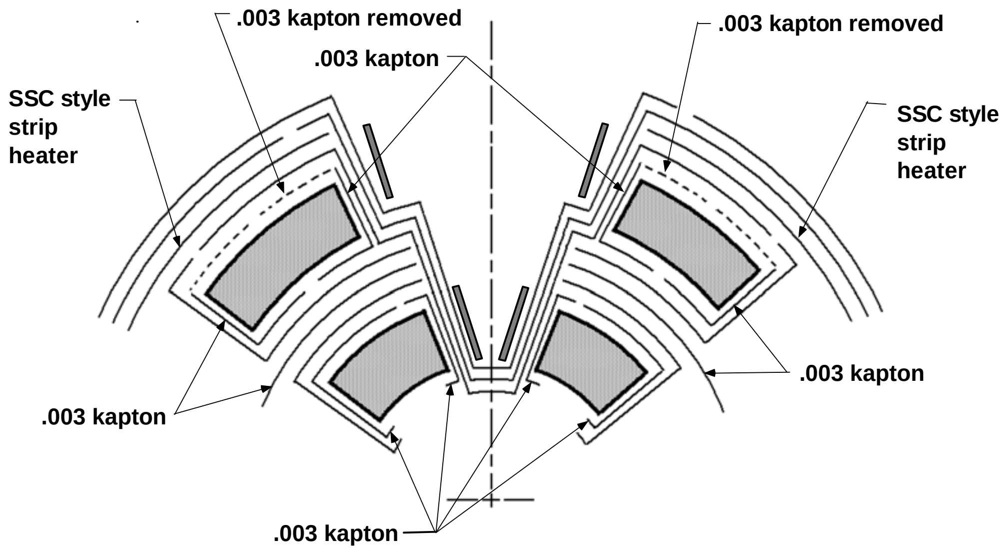


Figure 4.1.1 HGQ06 Coil Arrangement

4.2 Ground Wrap System

The coil insulation and ground wrap systems (body and ends respectively), for HGQ06 are shown in Figures 4.2.1 and 4.2.2. All layers of kapton are .005 inch (125uM) thick unless otherwise specified in the figures. One layer of .003 inch (75uM) kapton was removed between the outer coil and the collars to allow room for the .003 inch thick strip heater. One layer of .003 inch thick kapton was added between the inner and outer coils to take the place of the inter layer strip heater. The original design allowed for a strip heater between the inner and outer coils, but not between the outer coils and collars.

A complete description of the ground wrap system for HGQ06 is shown in drawing 5520-MC-



369292.

Figure 4.2.1 HGQ06 Body Coil and Ground Insulation System

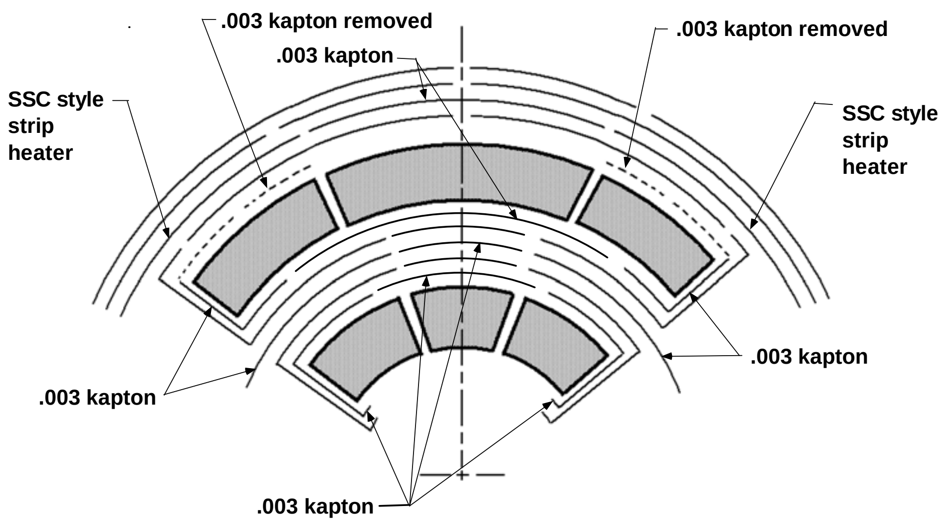


Figure 4.2.2 HGQ06 End Coil and Ground Insulation System

4.3 Strip Heaters

Quench protection (strip) heaters have, at various times, been placed in two different positions in High Gradient Quadrupoles, radially between the inner and outer coils, and between the outer coils and collars. Several different designs have also been used.

HGQ06 has no heaters between the inner and outer layers. SSC style heaters were used between the outer layers and collars. These heaters are the "single element" style, with copper plated stainless steel elements, ½ inch wide. The copper is etched away incrementally, exposing the stainless. The etched areas are 24 inches long, with 26 inch unetched sections between them. They were originally made for SSC long dipoles, and were modified for the HGQ magnets by cutting them to the proper length. Each strip was positioned longitudinally so that a 26 inch unetched section was placed at the center of the magnet, with a 24 inch etched section on each side.

The unmodified strip is described in detail in drawing #0102-MD-292218.

4.4. Pole splice.

The pole turn of each inner/outer coil pair needs to be spliced together. The internal splice configuration is used for HGQ-06. Splices are 114 mm long, which is approximately equal to the cable transposition pitch. Areas to be spliced are preformed, i.e., filled with solder, before the coil is wound. The tinned sections are then spliced after the coils are assembled on the mandrel.

The maximum temperature for the turn next to the heater during the splicing processes was about 60 C. A cooling fixture was attached at the coil side so that the coil is not heated up.

Splice insulation system is 25um x 9.5mm Kapton w/48% overlap surrounded by 50um x 9.5mm Kapton w/2mm gaps. Cooling channels were made in the G11 insulation spacers. The magnet then was surrounded by ground insulation.

5. Collaring and keying.

5.1 Collar pack.

Special collar pack was used to increase axial rigidity of the coil's body. The collar pack shown on Figure 5.1.1.

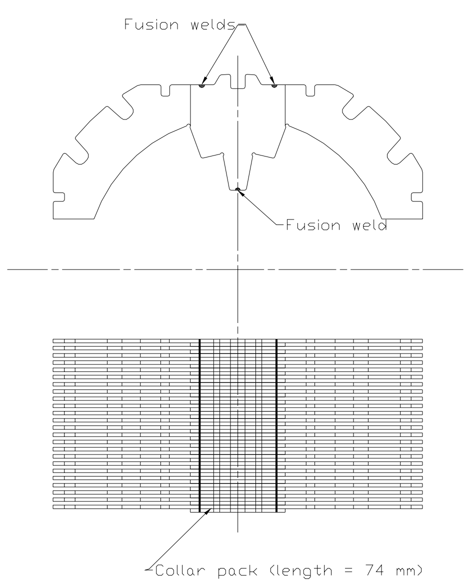


Figure 5.1.1. Collar pack.

Several different lengths of collar pack had been used, 74 mm (48 pieces), 75.5 mm (49 pieces), 72.5 mm (47 pieces), and 69.5 mm (45 pieces). Small bearing strips approximately the same length as packs were used. They were attached to the poles at the pack ends using 25 (0.001 in) thick adhesive Kapton tape. First and last packs were insulated at the ends to avoid coil-to-ground shorts, because no key extensions used in the magnet.

5.2. Collaring and keying procedure.

The magnet is packed starting from Return End using the vertical keying press (line pressure ~250 pump psi).

The collared assembly is “massaged” at 500, 1500 and 3000 pump psi of the main pressure (MP), partially keyed by hand at MP = 4500 pump psi. Final keying was done at MP=6750 pump psi using 3000 pump psi of the key pressure (KP). Short 3 in keys were used for keying. No shorts to ground during keying had been discovered.

Figure 5.2.1 shows pack’s location along the body and keying procedure in details.

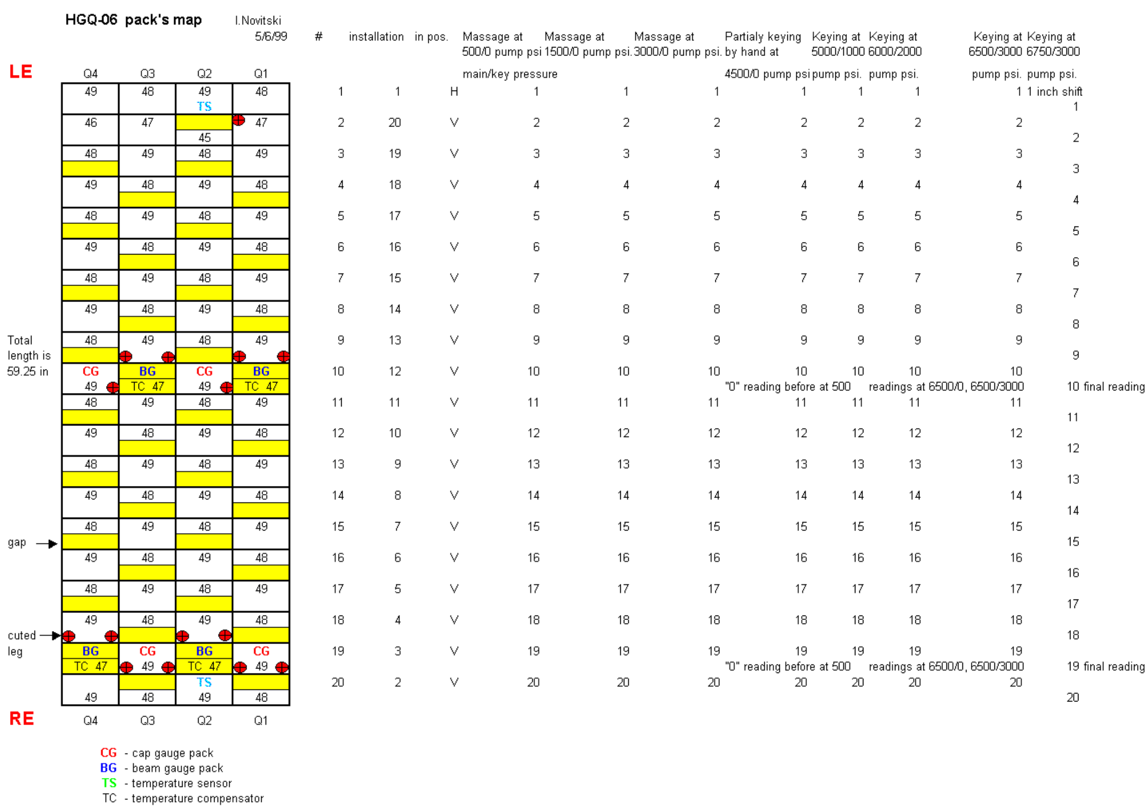


Figure 5.2.1. Map of packs and keying procedure.

5.3 Strain gauge readings

To achieve proper preload, the magnet was reassembled and 25um Kapton shims were added to the coils at pole region. During disassembly, the beam gauges yielded and are therefore not accurate.

The final pressures after magnet keying are shown in Tab. 5.4.1. The strain gauges nearer the lead end are designated “lead end” and the strain gauges nearer the return end are designated “ return end”, even though the gauges are within the body, and not actually at the lead or return end.

Cap gauges

		HGQ-06 final, MPa	HGQ-05 final, MPa
LE	inner	64	94
	inner	57	99
RE	inner	67	109
	inner	76	
LE	outer	73	
	outer	67	
RE	outer	50	84
	outer	82	

Beam gauges

		HGQ-06 final, MPa	HGQ-05 final, MPa
LE	outer	166	35
	outer	113	47
RE	outer	139	64
	outer	133	54

Table 5.3.1. Final pressures. (with HGQ05 pressures shown for comparison)

5.4 Mechanical measurements.

The OD measurement data for collared coil block (Fig.5.4.1) show on Fig. 5.4.2-5.4.4. The 3 extra points (connected by straight lines) were taken by hand after mandrel pulled out.

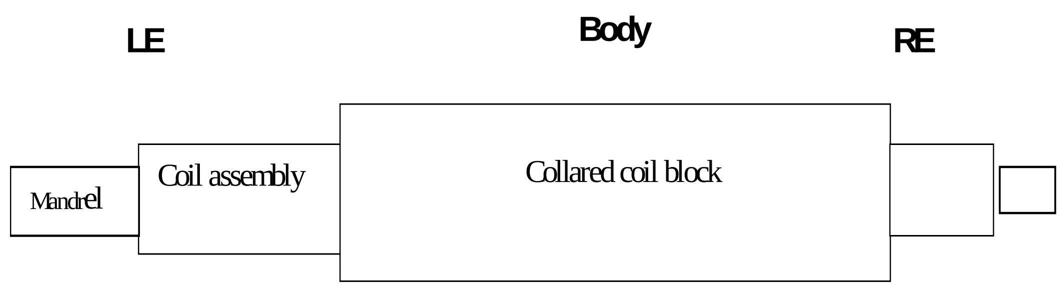
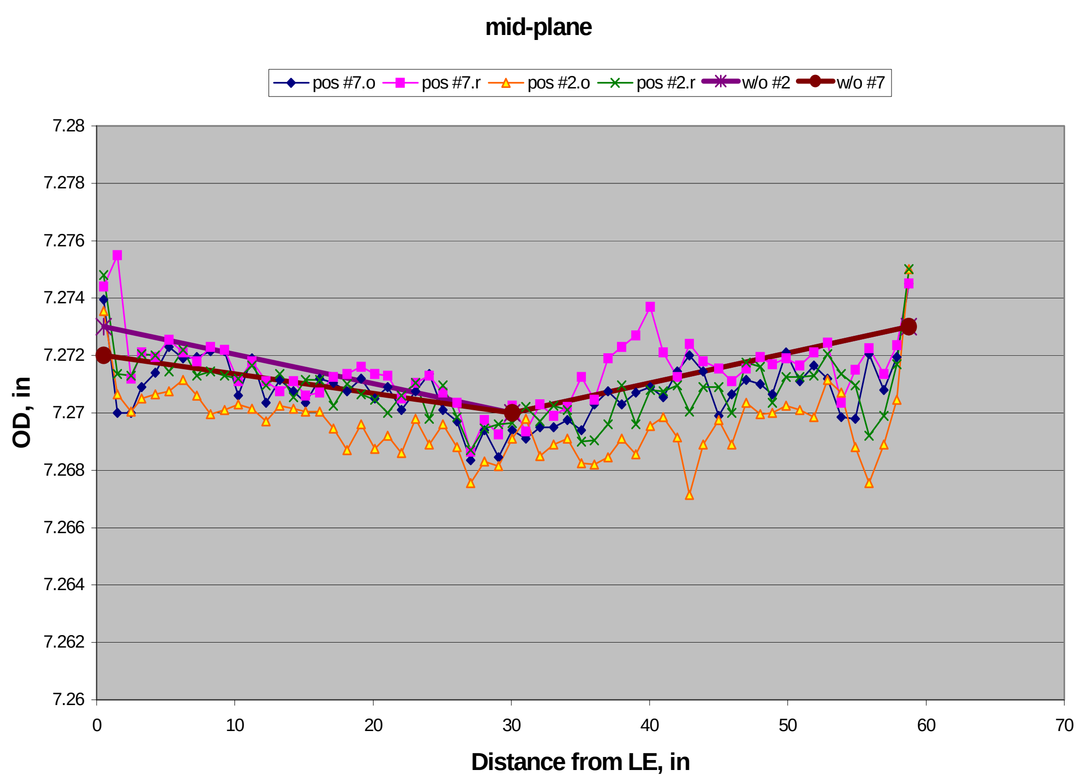


Figure 5.4.1. Collared coils with coil assembly on the mandrel.



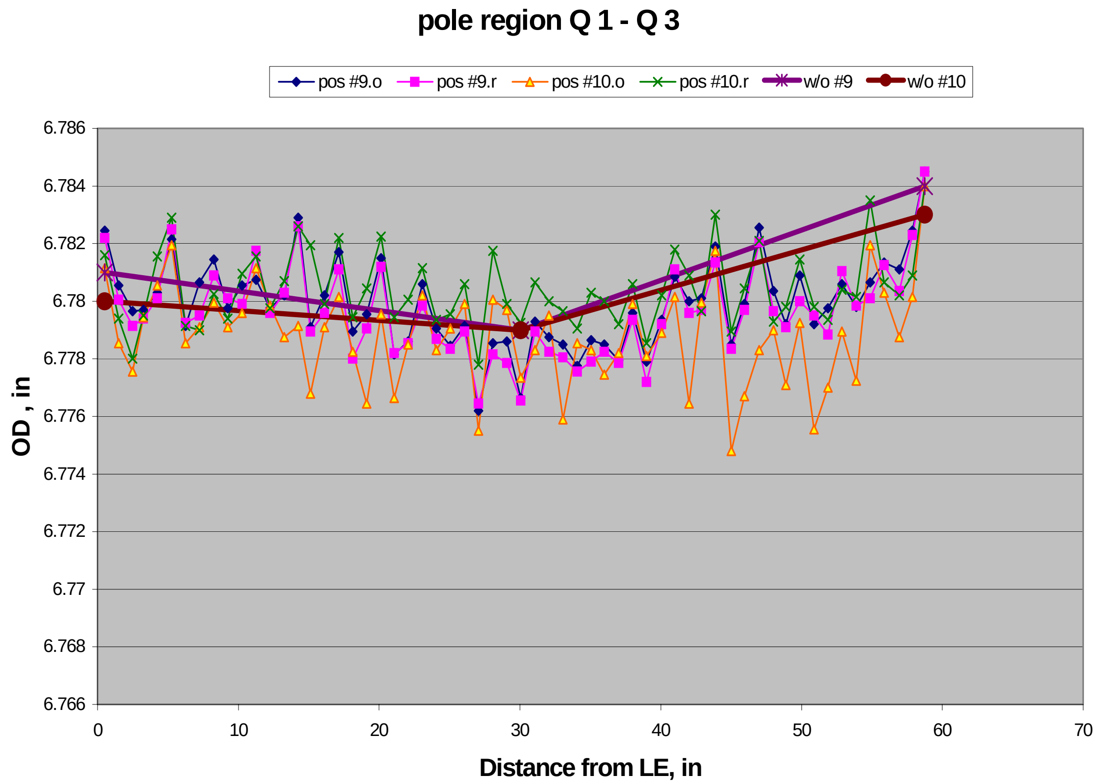


Figure 5.4.2. Collared coil deflections at midplane region.

Figure 5.4.3. Collared coil deflections at pole region, pos#9,10.

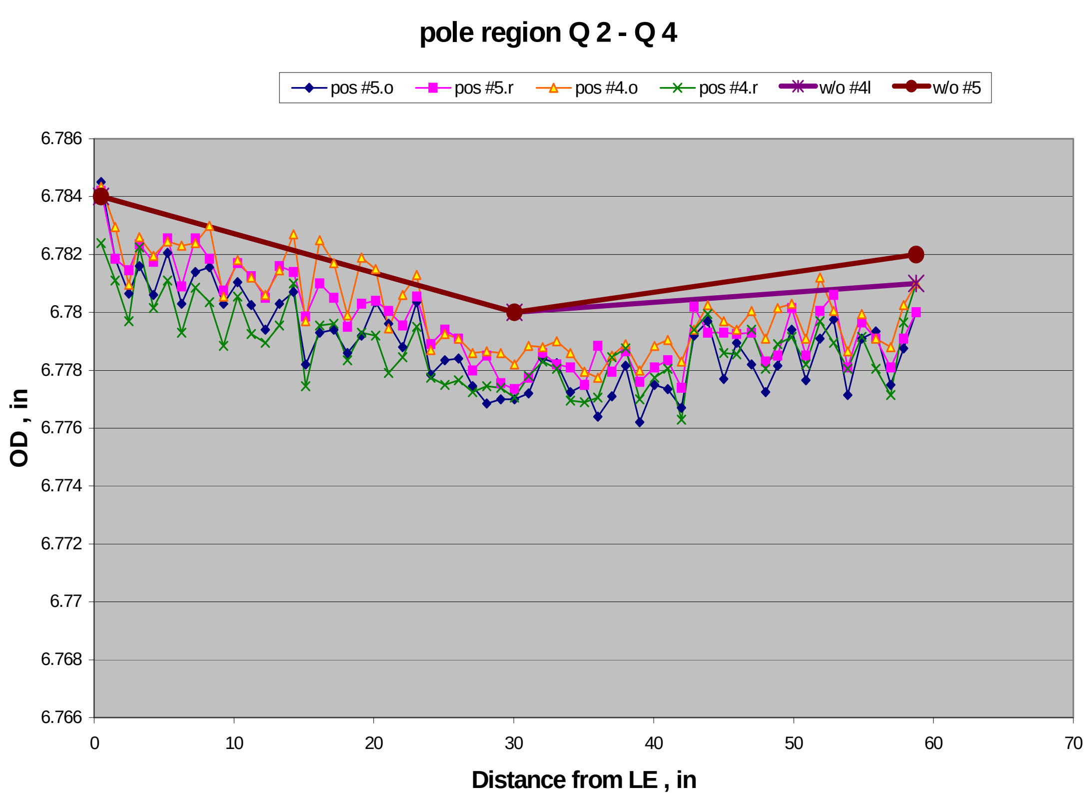


Figure 5.4.4. Collared coil deflections at pole region, pos#4,5.

6.0 End Clamps

6.1 Installation Procedure:

HGQ-06 has end cans at both LE and RE. Due to the new configuration of the end parts (5-block design instead of 4-block), the length of the end cans were modified compared to the HGQ-05 ones. The LE can is 9.833 inch and RE can is 5.194 inch long for HGQ-06. G-11 filler cones were used instead of G-10, the idea was to match the material of end-parts and end can filler cones. G-11 end parts were used for the coils instead of G-10.
Fuji film tests were performed before final installation. The results of the Fuji film readings showed that there is a uniform radial pressure distribution from the transition region to the end-saddle for both LE and RE.

6.2 Measurements and Shimming:

The medium range Fuji film thickness is 4 mil and the Fuji film readings were taken without removing any designed ground insulation layer. The pi-tape measurements and film readings showed desired results. It is then decided to increase the thickness of radial ground insulation surrounding the outer coil by 3 mil at both ends from the original design. The radial deflection of the aluminum end can according pi-tape measurements is shown below: (target diameter change from FEA, was 10 ~ 12 mil)

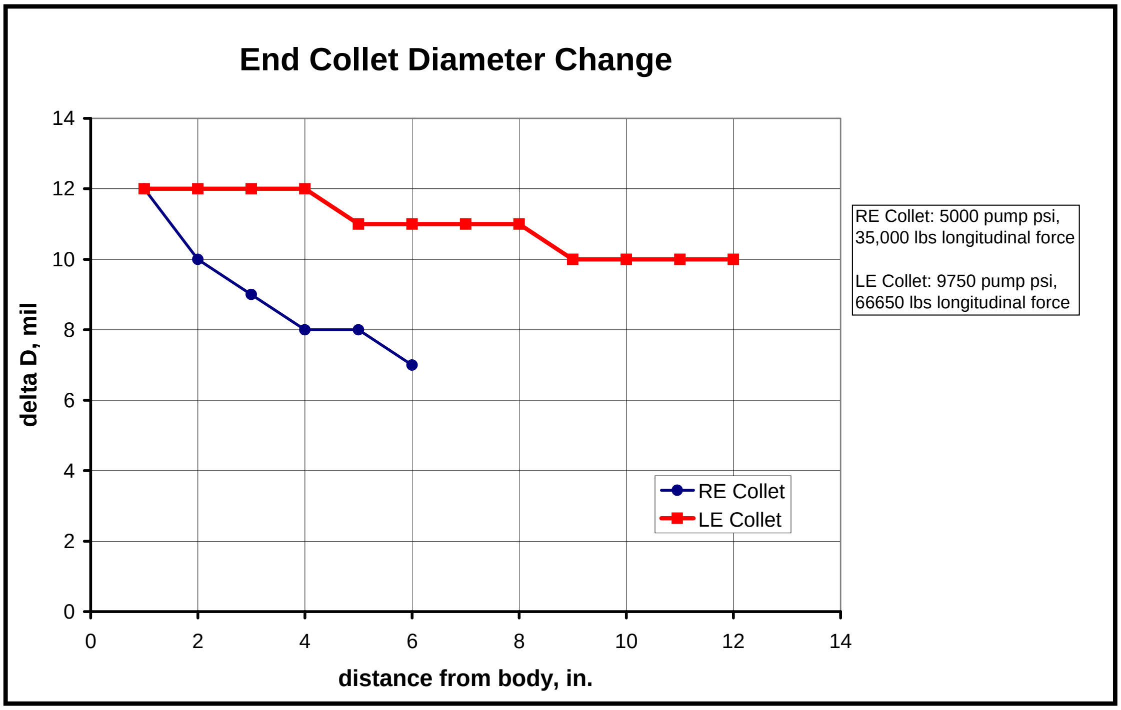


Fig 6.2.1: Aluminum End Can Radial Deflection

7.0 Yoke and Skinning

7.1 Assembly Configuration:

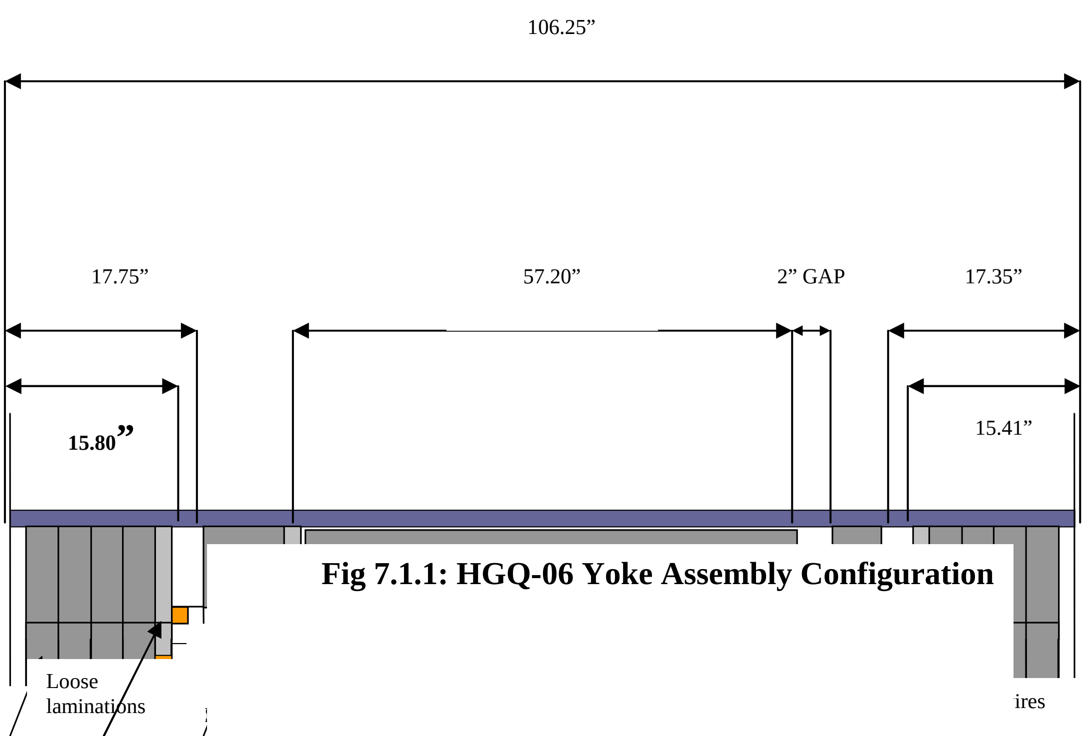


Fig 7.1.1: HGQ-06 Yoke Assembly Configuration

All lamination packs were fusion welded longitudinally in 7 places (5 welds on outer surface and 2 welds on inner surface). There was a problem with HGQ-06 welded body packs. Instead of a fusion weld, in one spot the welder applied a filler weld. It is decided that this can cause a problem magnetically for the magnet.

HGQ-01 welded body yoke lamination pack [ME-344596] was used for HGQ-06. They were inspected and it is found out that they are suitable to use for HGQ-06. Stainless steel modified yoke laminations were used for RE and LE. These laminations were modified at the pole with EDM to fit over the LE and RE can. The above figure shows the length and the layout of the yoke laminations during assembly. The LE and RE yoke lamination length is different that HGQ-05 due to the end part configuration change (4 block to 5 block)

7.2 Welding:

The skin alignment key was unintentionally 23.5 mm wide for HGQ-06. This is 0.5 mm narrower than HGQ-05 and HGQ-03. This leaves a gap of 1.25 mm between the yoke and the skin. The magnet was compressed at 600 PSI during welding. The magnet was compressed in the weld tooling with a hydraulic pressure of 600 PSI corresponded to force about 8000 lbs. (3600 kg) per pusher or 16000 lbs./ft (23700 kg/meter) of magnet length. A pressure above 500 PSI must be applied to completely collapse the springs in the wheel units of the bottom tooling. The distance between the top and bottom pushers was measured from both the north and south side of the press all along the length of the magnet. The below graph shows these results:

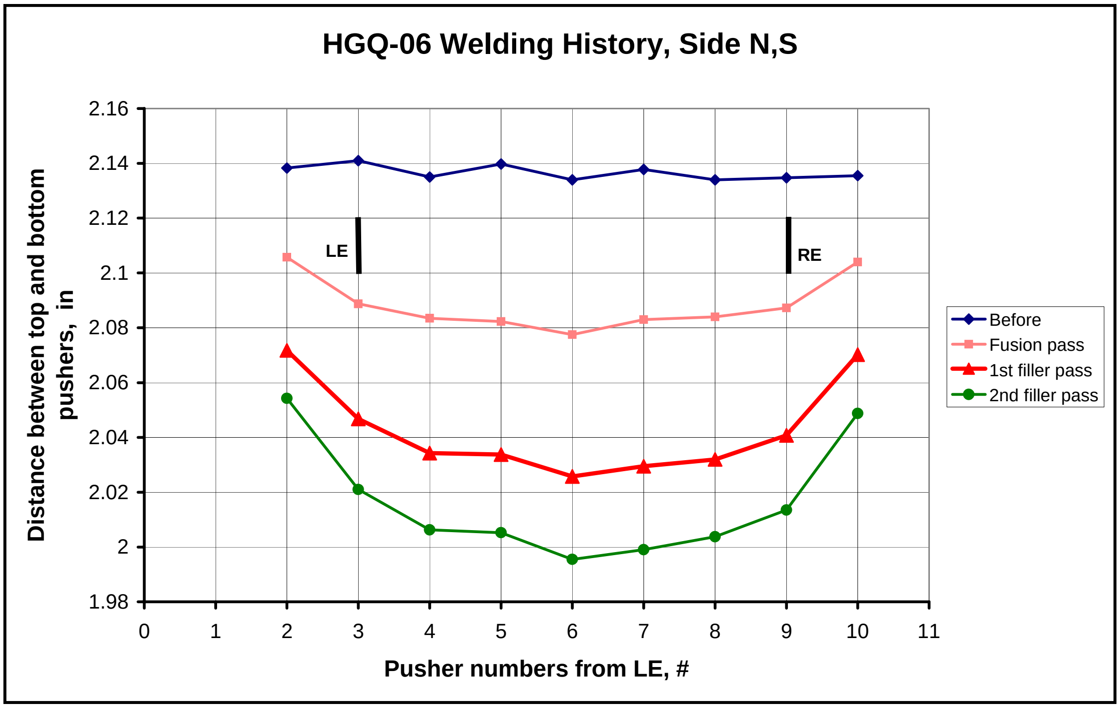


Fig 7.2.1: Weld Shrinkage for HGQ-06 with 23.5 mm key

The same procedure followed for HGQ-05 skin welding is repeated for HGQ-06. The first pass was a fusion and consecutively two filler passes were applied. More then filling the weld route, the shrinkage was monitored and it was the criteria for weld quality. Whenever the same amount of shrinkage was achieved for HGQ-06 as HGQ-05, the welding was stopped.

After the welding was completed, the magnet was transported back to IB3 from ICB. The skin was cut to the exact length. After the routing of instrumentation wires were completed, the end plates were welded. The RE end plate was modified with small channels around the cooling holes to accommodate the instrumentation wires for the RE axial preload bolts.

The skin OD measurements were taken at different angles after the end plate welding. The following graph shows the results of this measurement:

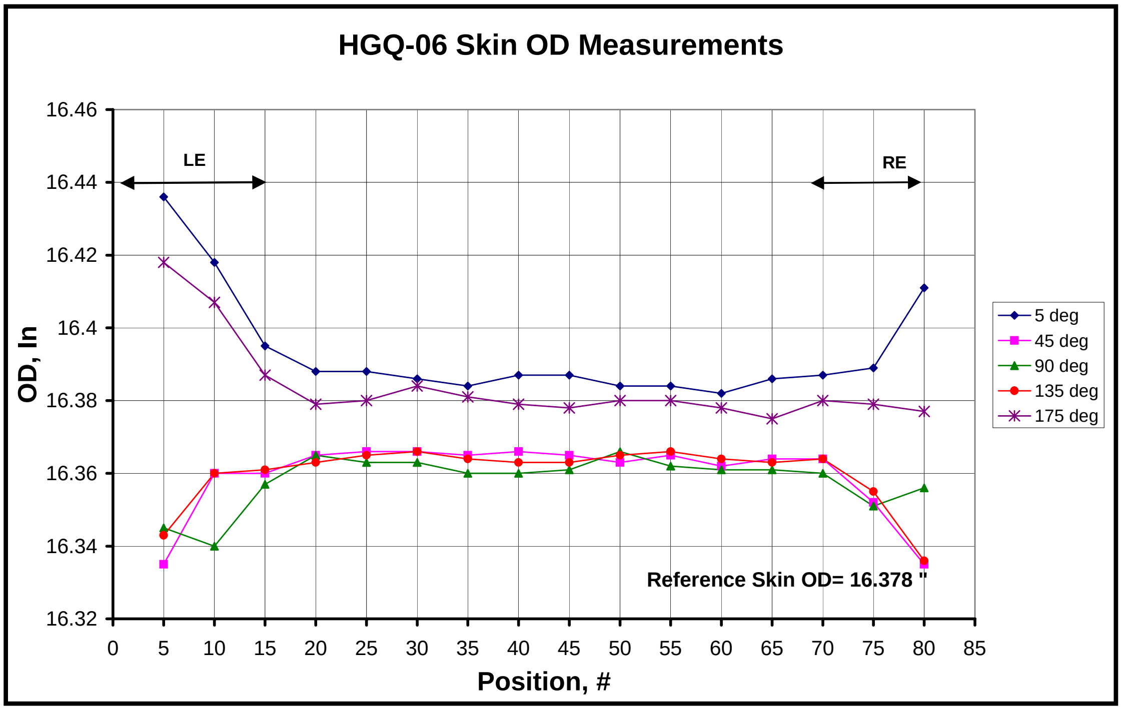


Fig 7.2.2: Skin outer diameter according to micrometer measurements taken at different angular positions between skin alignment keys

7.3 OD and Twist Measurements:

The twist in the cold-mass assembly after welding the skin and the end plates was measured with a height gauge and twist-measuring device. The twist is measured as 1.0 milli-radian per meter in the straight section of the magnet. The twist in HGQ-01 was 4.67 milli-radian per meter, for HGQ-02 it was 0.6 milli-radian per meter, for HGQ-03 it was 1.0 milli-radian per meter and for HGQ-05 it was measured as 0.9 milli-radian per meter. The direction of the twist is same in all the four magnets and is clockwise looking from LE to RE. The below graphs show the height gauge measurements and respective twist measurements with height gauge and twist measuring device in milli-radians.

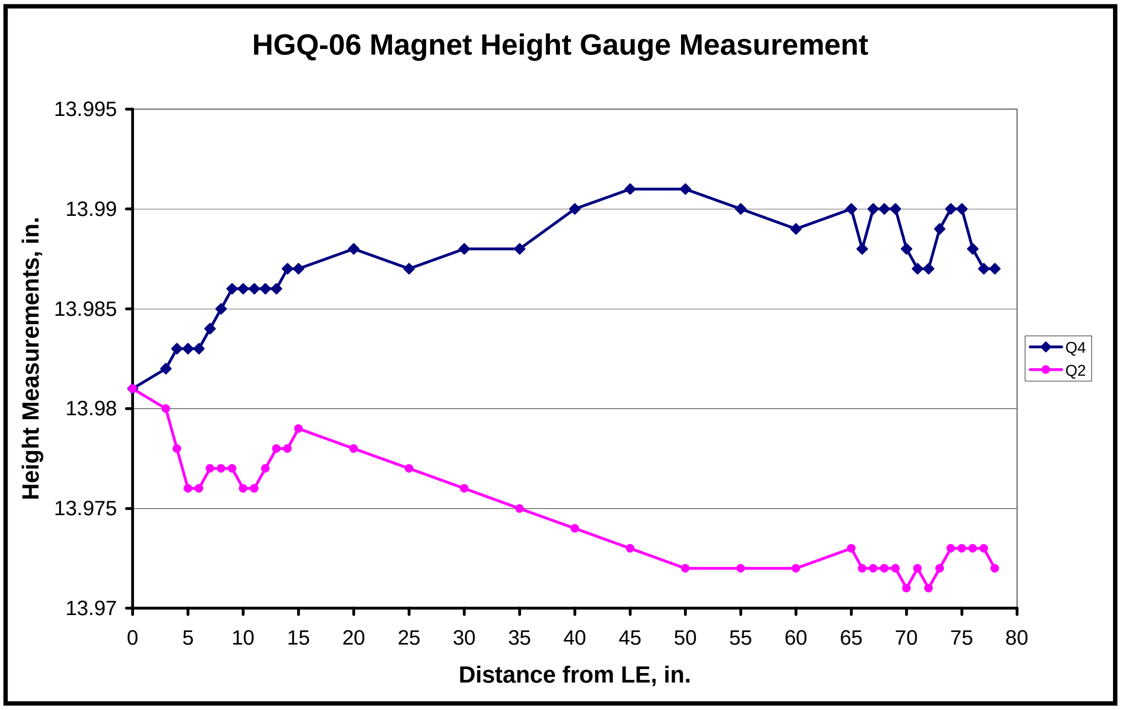


Fig 7.3.1: Height Gauge Measurements taken in Quadrant 2 and 4 for HGQ-06

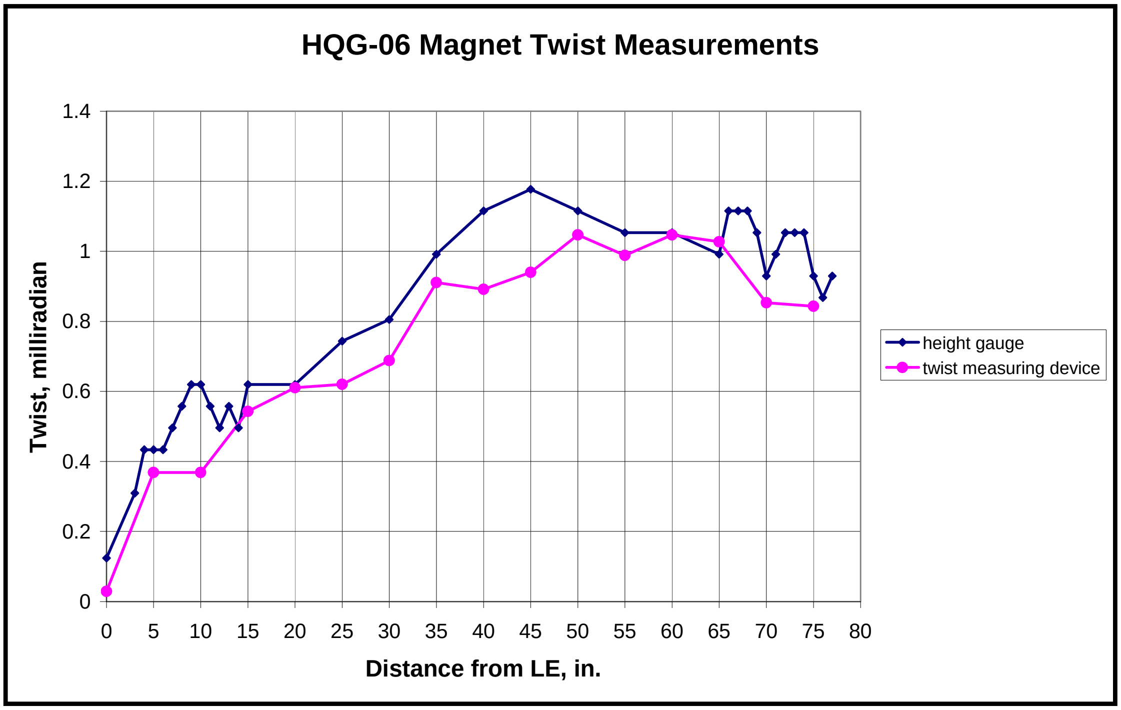


Fig 7.3.2: HGQ-06 Cold Mass Assembly Twist Measurements

7.4 Axial Loading (Bullets & Bolts):

The axial support system of the magnet is shown below:

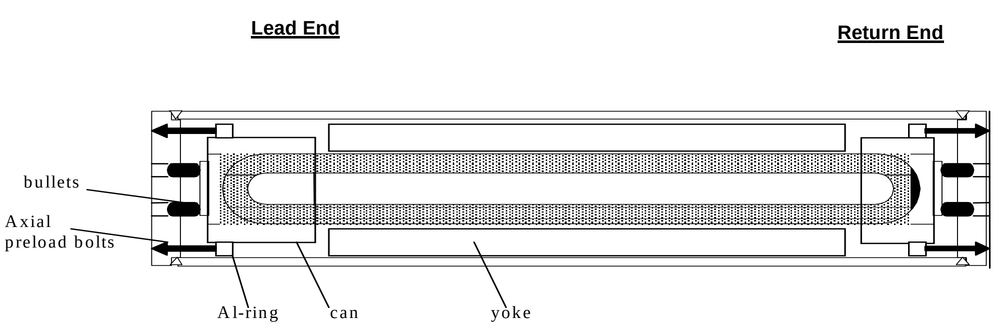


Fig 7.4.1: Axial Support of the Cold Mass Assembly

The end load has been applied by touching the bullets to the solid pusher plate, then tightening the bolts. The gaps between coil end-saddles and pusher plate was filled by "green putty". This time, the bolts were also instrumented to measure the force during loading, as were the bullets. Bullets were warm and cold calibrated. Bolts were warm calibrated and only two of them were cold calibrated due to time restriction. The LE bolts were tightened first and a 3.5-mil travel is recorded at the RE. The torque sequence for each loading phase is shown in the following charts:

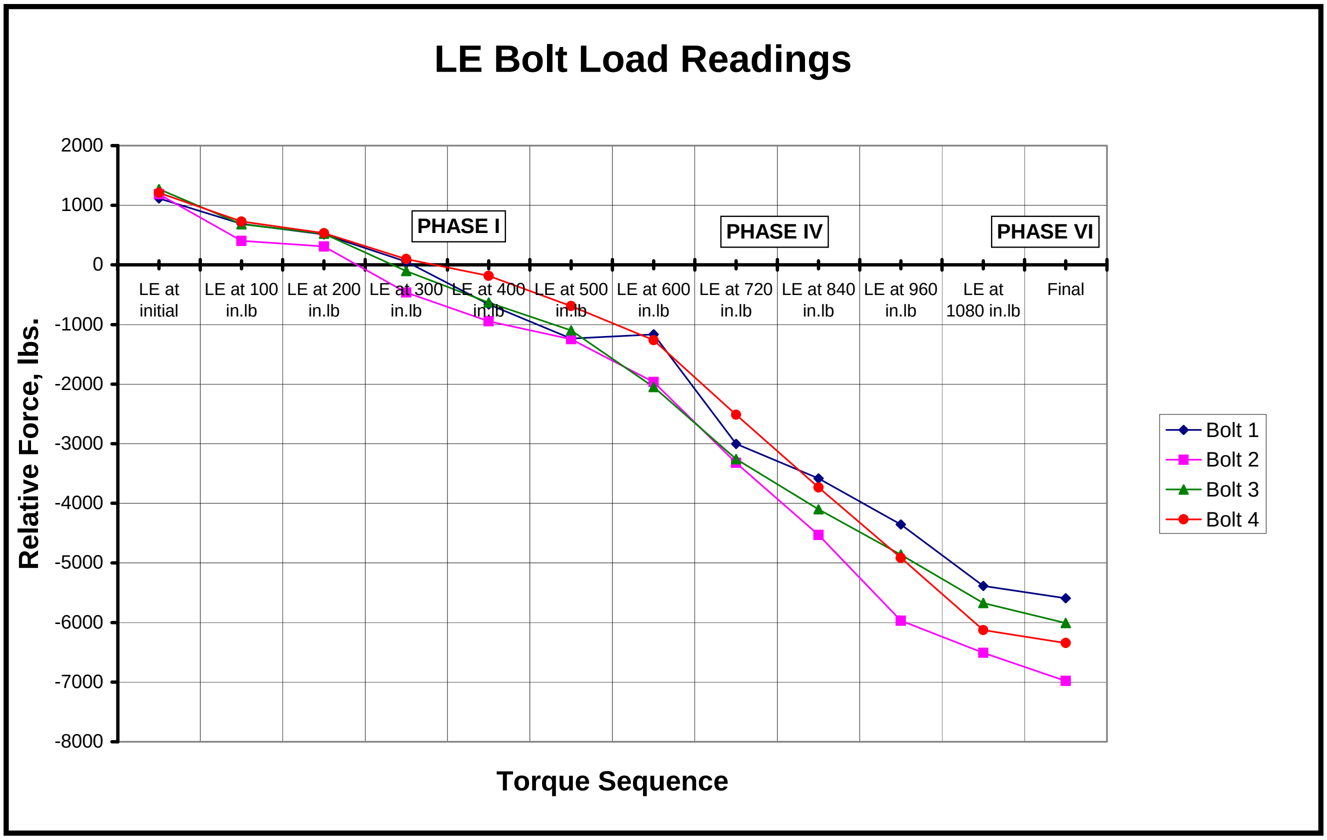
Loading Phases:

Before starting, all bullets were "hand tightened".

Phase 1: *LE bolts were torqued from 0 to 600 in.lbs, Delta RE is 3.5 mil*
Phase 2: *RE bolts were torqued from 0 to 600 in.lbs*
Phase 3: *RE were torqued from 600 to 960 in.lbs after RE bullet adjustment*
Phase 4: *LE bolts were torqued from 600 to 1080 in.lbs after LE bullet adjustment*
Phase 5: *RE bolts were torqued to 1080 in.lbs*
Phase 6: *LE and RE bullets were adjusted*

A total of 2200 lbs. of force was applied to the bullets at both RE and LE at the end of phase 6. The load bolts readings were 8000 lbs. at both ends. The next day readings showed a decrease of 100 lbs. at the bullets. Because the total force was still over 2000 lbs., it is decided to leave it as it is. The total axial force on the load bolts is 6000-lbs. tension at both LE and RE.

The bullet readings were good at warm conditions as usual. The new data collected with load bolts also agreed with the applied torque. A force-torque relation map was generated using ¾"-10 dia. Threaded 18-80 Stainless Steel bolt. The measured force matched with the calculated one closely. Because the bolts were calibrated under compression and during axial loading, they were always under tension, the data was decreasing with the increased torque, but after the interpretation of the data, the results looked good for both bullets and load bolts.



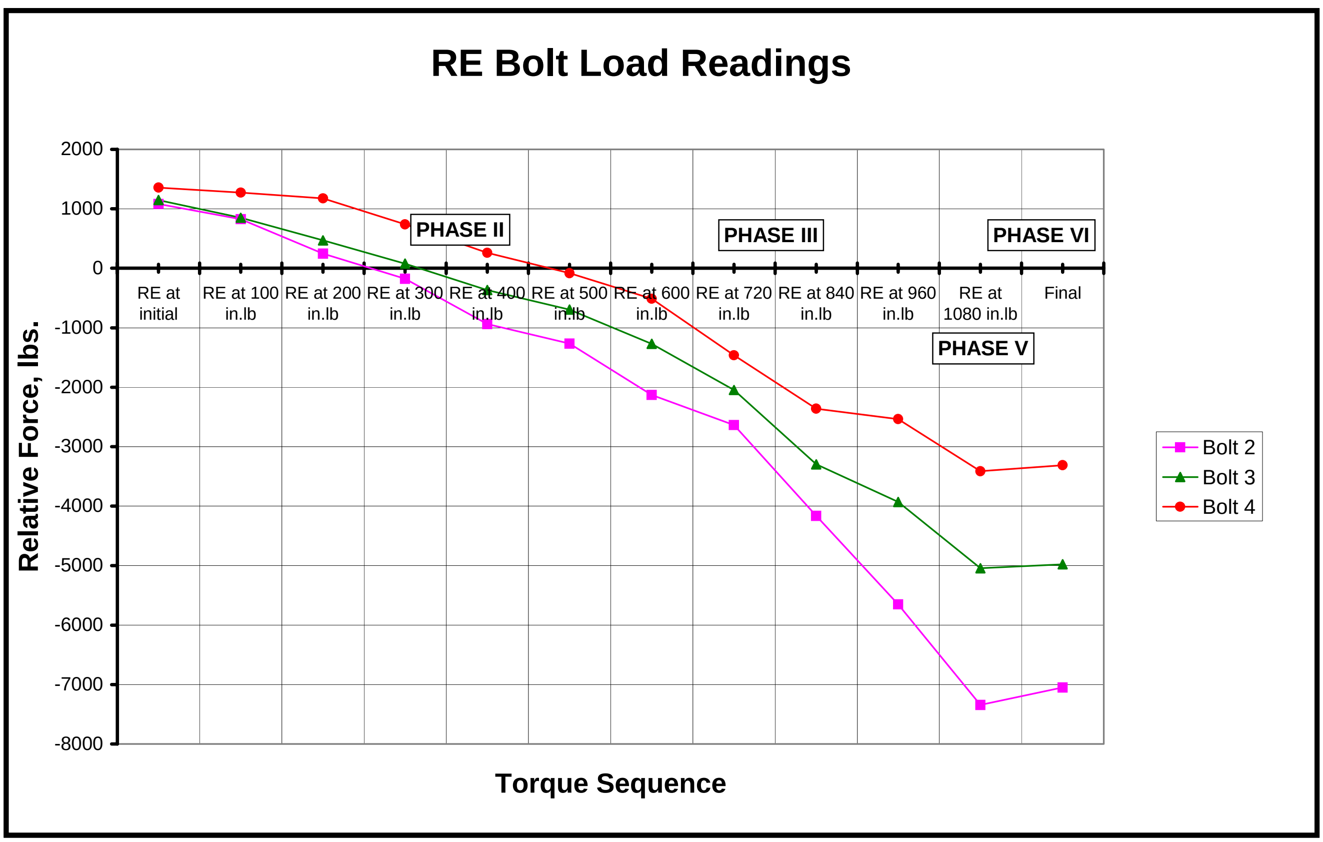
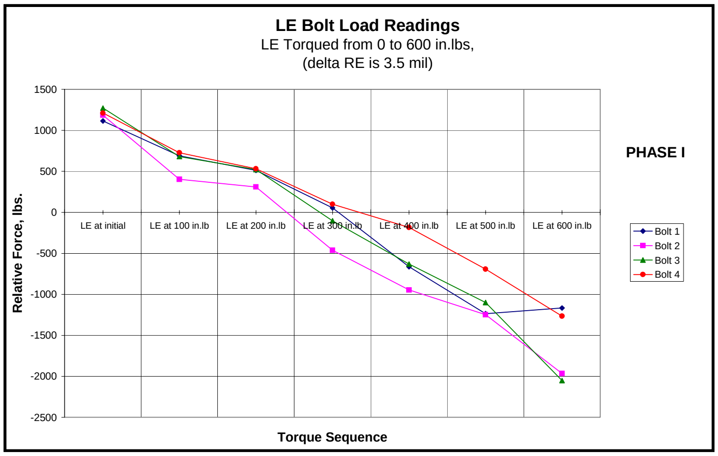
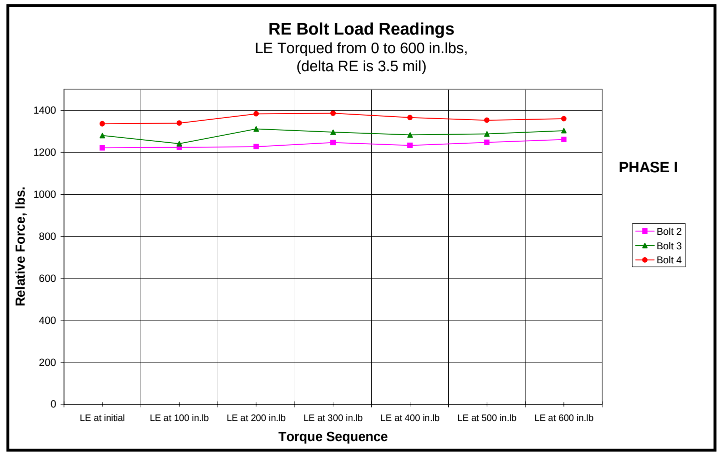
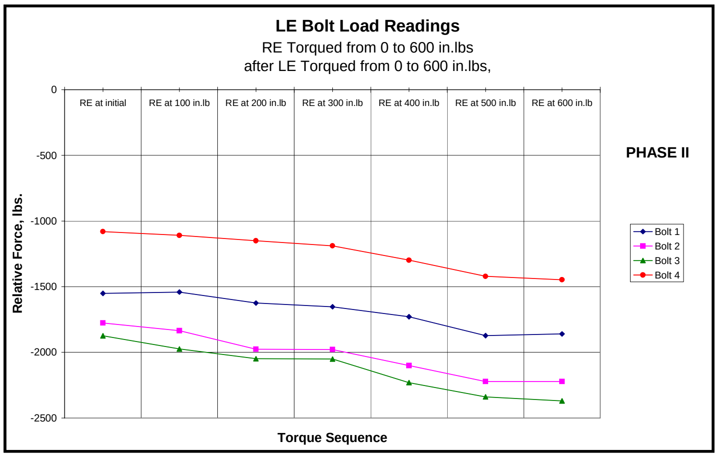
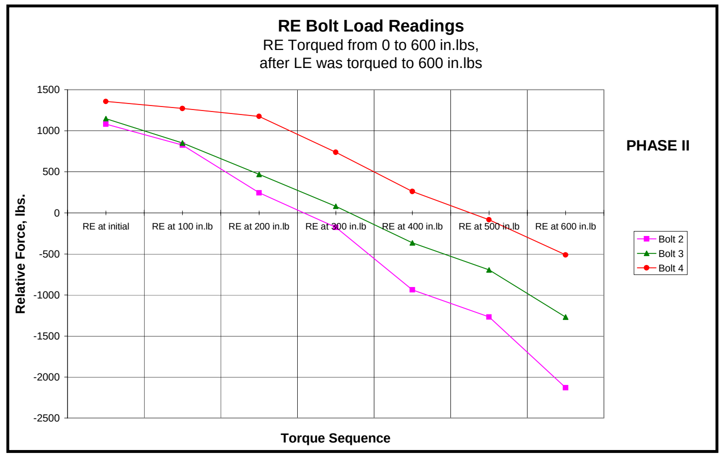


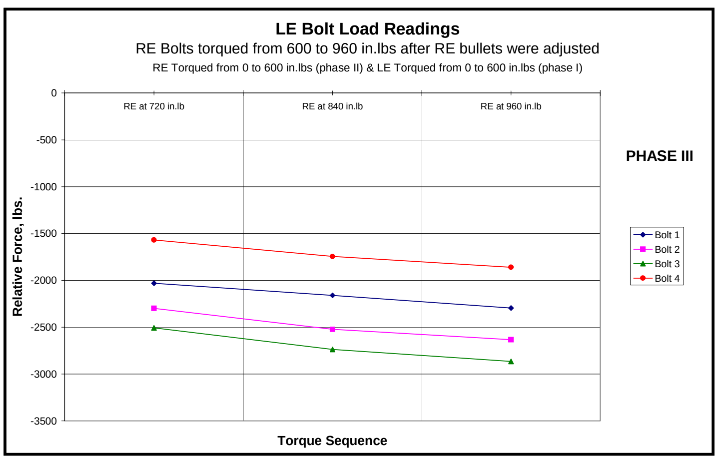
Fig 7.4.2: Axial Preload Bolt Readings for RE and LE at different Torque Phases

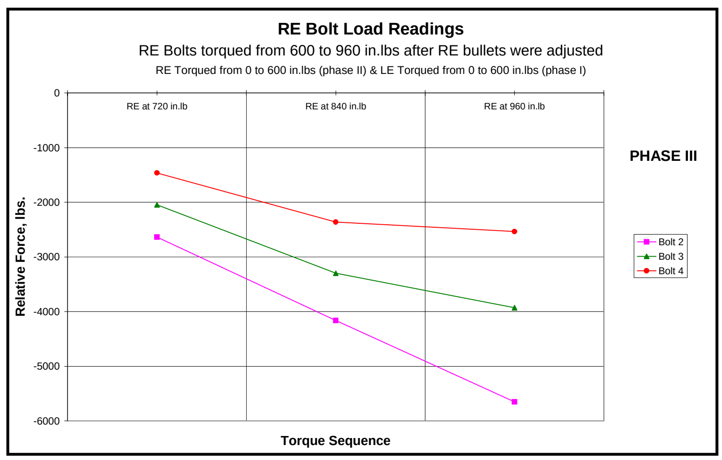

LE Bolt Load Readings
LE Torqued from 0 to 600 in.lbs,
(delta RE is 3.5 mil)
PHASE I
Relative Force, lbs.
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
LE at initial
LE at 100 in.lb
LE at 200 in.lb
LE at 300 in.lb
LE at 400 in.lb
LE at 500 in.lb
LE at 600 in.lb
Torque Sequence
Bolt 1
Bolt 2
Bolt 3
Bolt 4

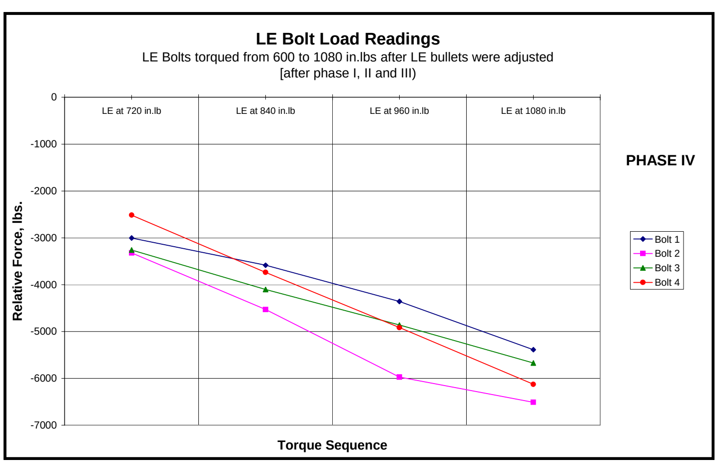

RE Bolt Load Readings
LE Torqued from 0 to 600 in.lbs,
(delta RE is 3.5 mil)
PHASE I
Relative Force, lbs.
1400
1200
1000
800
600
400
200
0
LE at initial
LE at 100 in.lb
LE at 200 in.lb
LE at 300 in.lb
LE at 400 in.lb
LE at 500 in.lb
LE at 600 in.lb
Torque Sequence
Bolt 2
Bolt 3
Bolt 4

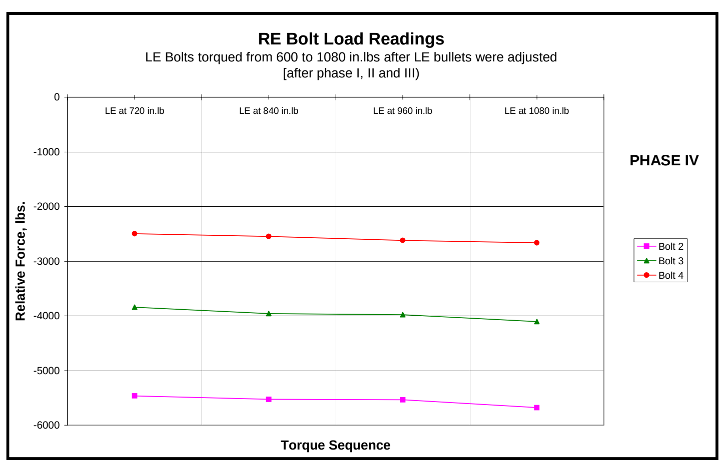

LE Bolt Load Readings
RE Torqued from 0 to 600 in.lbs
after LE Torqued from 0 to 600 in.lbs,
PHASE II
Relative Force, lbs.
0
-500
-1000
-1500
-2000
-2500
RE at initial
RE at 100 in.lb
RE at 200 in.lb
RE at 300 in.lb
RE at 400 in.lb
RE at 500 in.lb
RE at 600 in.lb
Torque Sequence
Bolt 1
Bolt 2
Bolt 3
Bolt 4

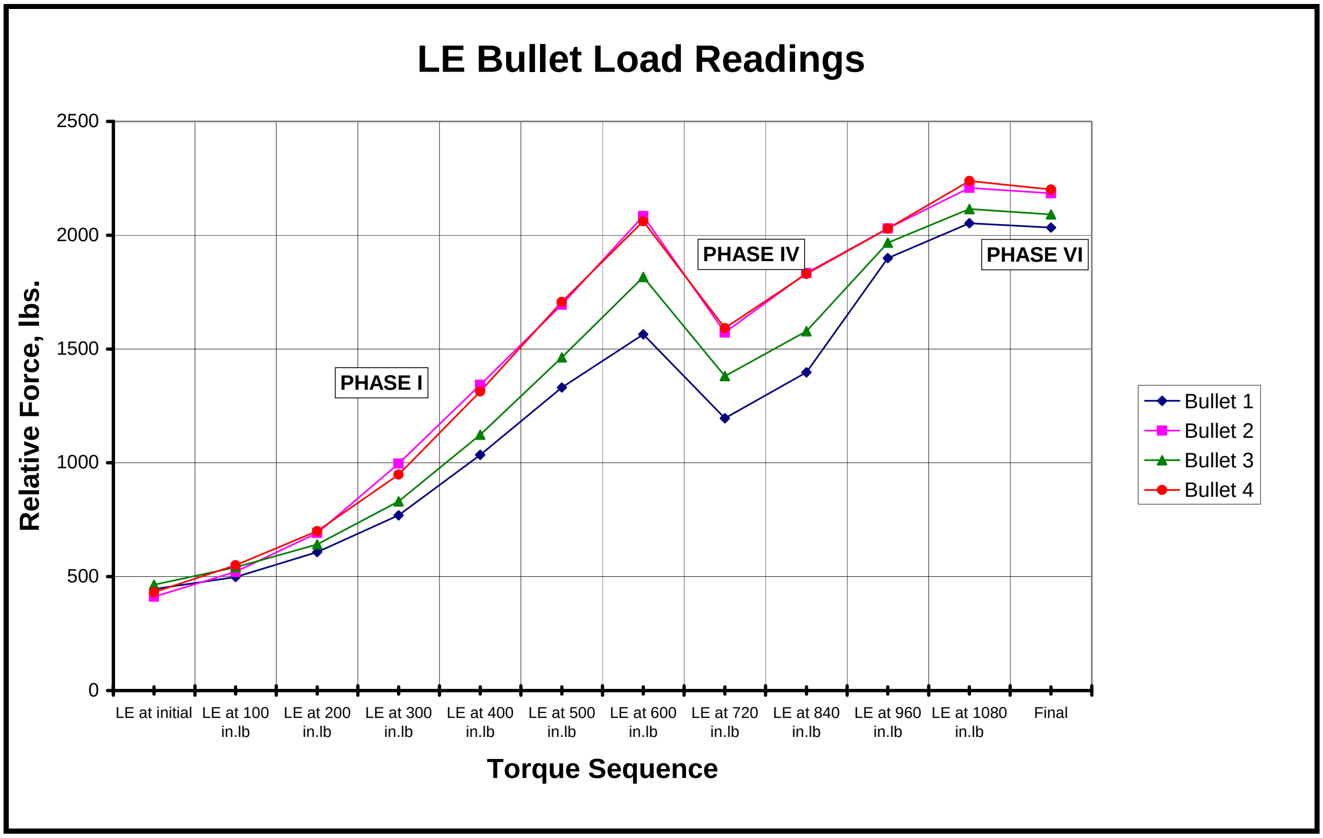

RE Bolt Load Readings
RE Torqued from 0 to 600 in.lbs,
after LE was torqued to 600 in.lbs
PHASE II
Relative Force, lbs.
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
RE at initial
RE at 100 in.lb
RE at 200 in.lb
RE at 300 in.lb
RE at 400 in.lb
RE at 500 in.lb
RE at 600 in.lb
Torque Sequence
Bolt 2
Bolt 3
Bolt 4


LE Bolt Load Readings
RE Bolts torqued from 600 to 960 in.lbs after RE bullets were adjusted
RE Torqued from 0 to 600 in.lbs (phase II) & LE Torqued from 0 to 600 in.lbs (phase I)
PHASE III
Relative Force, lbs.
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
RE at 720 in.lb
RE at 840 in.lb
RE at 960 in.lb
Torque Sequence
Bolt 1
Bolt 2
Bolt 3
Bolt 4


RE Bolt Load Readings
RE Bolts torqued from 600 to 960 in.lbs after RE bullets were adjusted
RE Torqued from 0 to 600 in.lbs (phase II) & LE Torqued from 0 to 600 in.lbs (phase I)
PHASE III
Relative Force, lbs.
0
-1000
-2000
-3000
-4000
-5000
-6000
RE at 720 in.lb
RE at 840 in.lb
RE at 960 in.lb
Torque Sequence
Bolt 2
Bolt 3
Bolt 4


LE Bolt Load Readings
LE Bolts torqued from 600 to 1080 in.lbs after LE bullets were adjusted
[after phase I, II and III)
PHASE IV
Relative Force, lbs.
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
LE at 720 in.lb
LE at 840 in.lb
LE at 960 in.lb
LE at 1080 in.lb
Torque Sequence
Bolt 1
Bolt 2
Bolt 3
Bolt 4


RE Bolt Load Readings
LE Bolts torqued from 600 to 1080 in.lbs after LE bullets were adjusted
[after phase I, II and III)
PHASE IV
Relative Force, lbs.
0
-1000
-2000
-3000
-4000
-5000
-6000
LE at 720 in.lb
LE at 840 in.lb
LE at 960 in.lb
LE at 1080 in.lb
Torque Sequence
Bolt 2
Bolt 3
Bolt 4



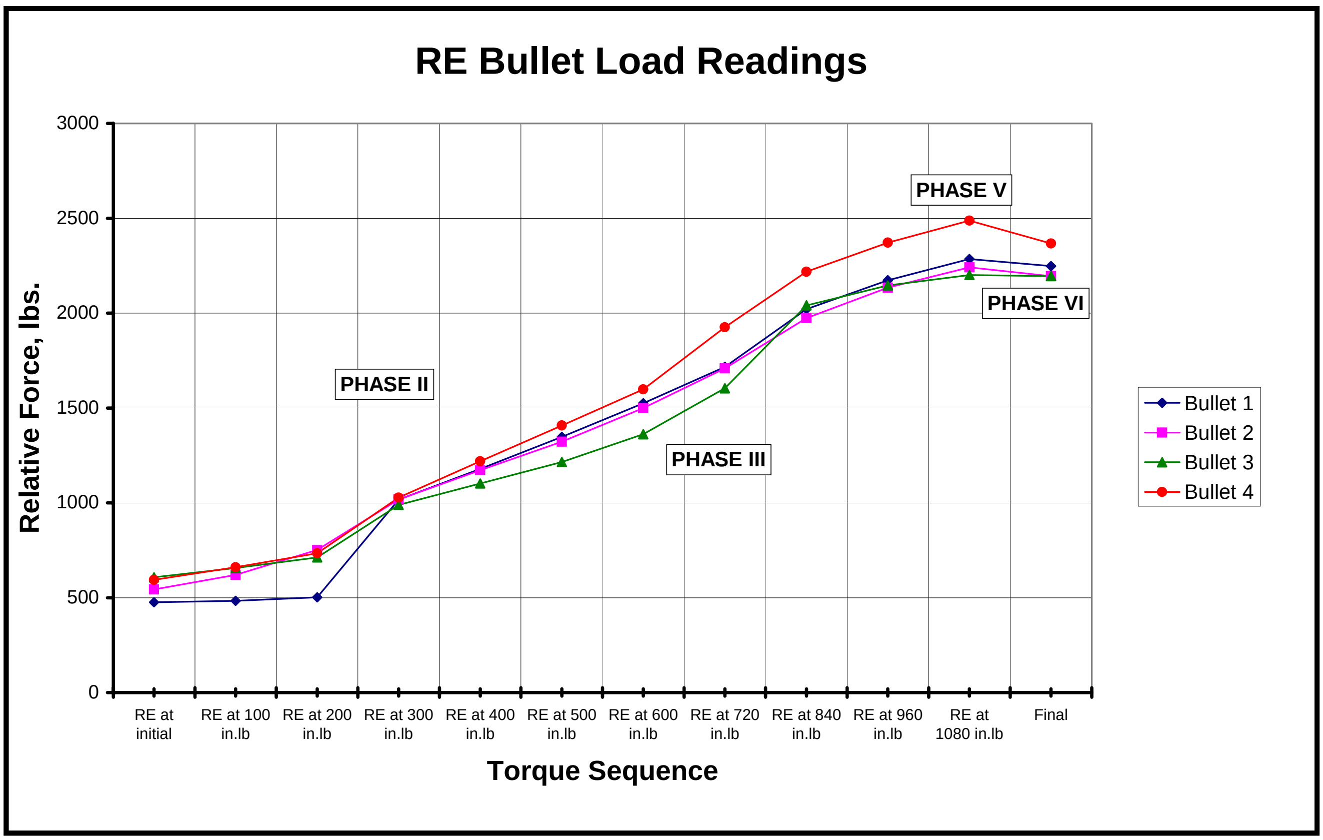
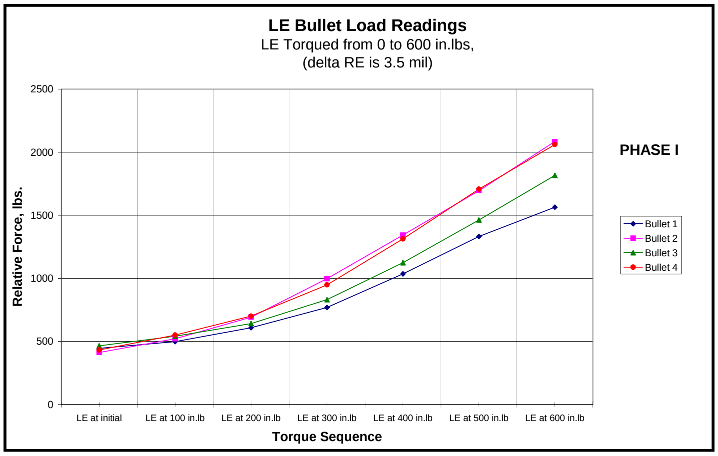
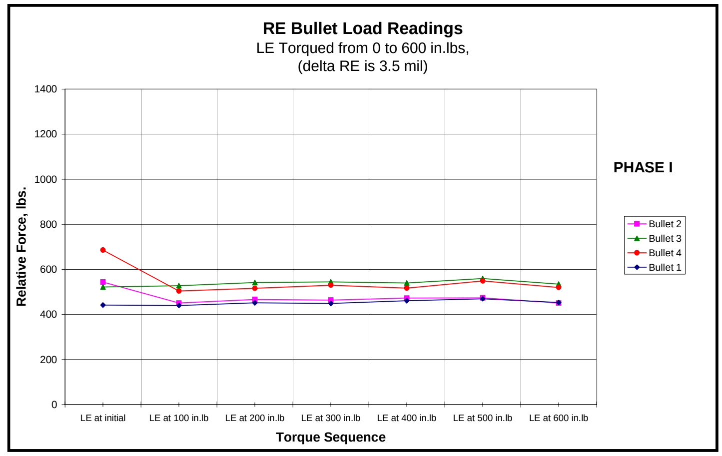
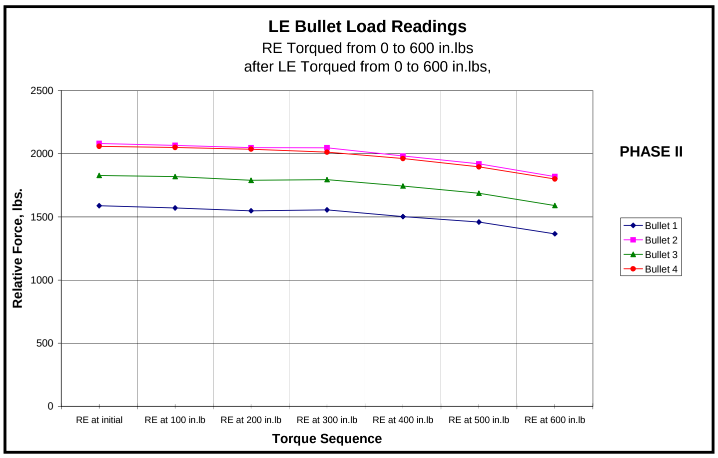
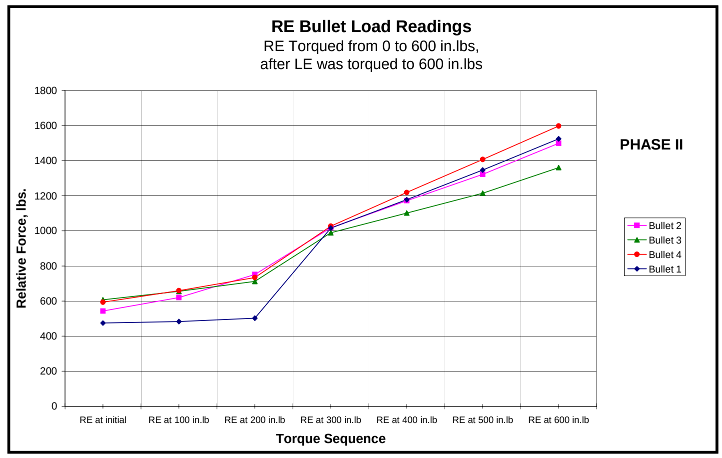


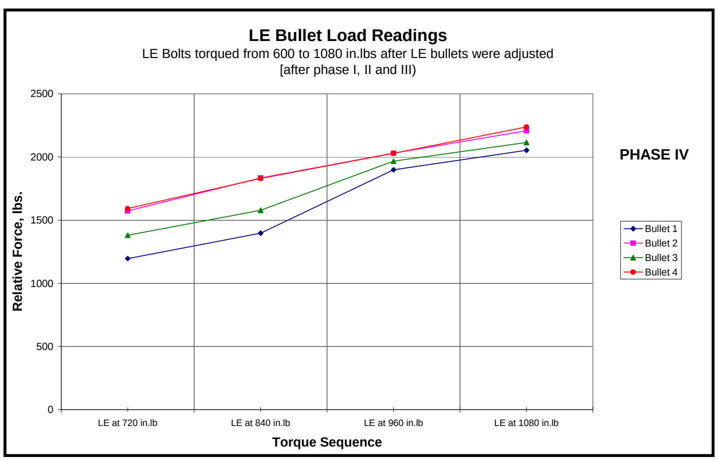
Fig 7.4.3: Bullet Readings for RE and LE at different Torque Phases

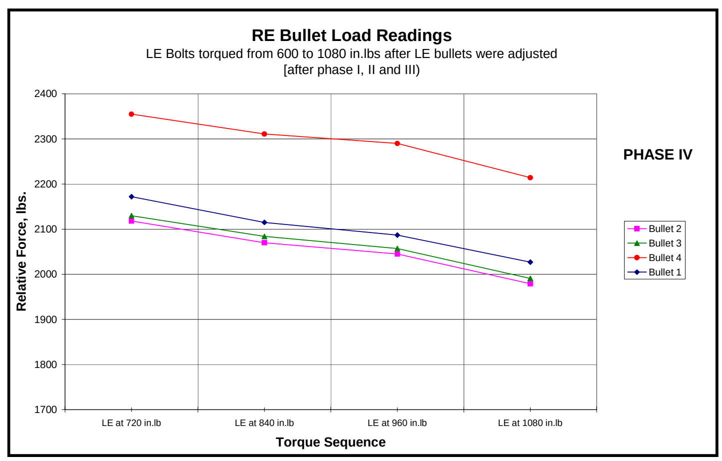

LE Bullet Load Readings
LE Torqued from 0 to 600 in.lbs,
(delta RE is 3.5 mil)
PHASE I
Relative Force, lbs.
Torque Sequence
LE at initial
LE at 100 in.lb
LE at 200 in.lb
LE at 300 in.lb
LE at 400 in.lb
LE at 500 in.lb
LE at 600 in.lb
Bullet 1
Bullet 2
Bullet 3
Bullet 4

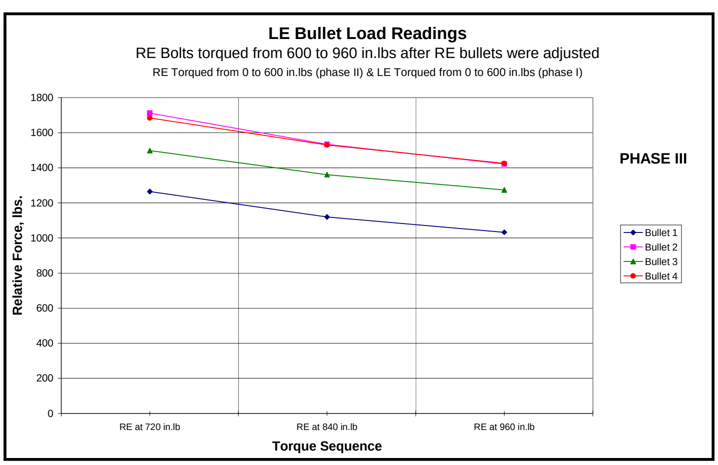

RE Bullet Load Readings
LE Torqued from 0 to 600 in.lbs,
(delta RE is 3.5 mil)
PHASE I
Relative Force, lbs.
Torque Sequence
LE at initial
LE at 100 in.lb
LE at 200 in.lb
LE at 300 in.lb
LE at 400 in.lb
LE at 500 in.lb
LE at 600 in.lb
Bullet 2
Bullet 3
Bullet 4
Bullet 1

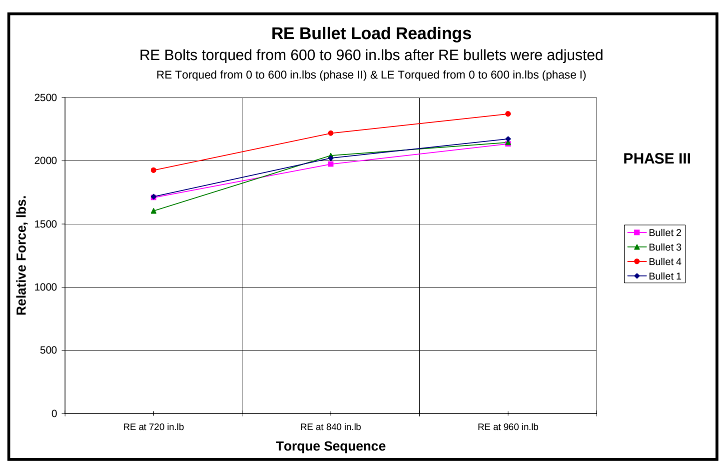

LE Bullet Load Readings
RE Torqued from 0 to 600 in.lbs
after LE Torqued from 0 to 600 in.lbs,
PHASE II
Relative Force, lbs.
Torque Sequence
RE at initial
RE at 100 in.lb
RE at 200 in.lb
RE at 300 in.lb
RE at 400 in.lb
RE at 500 in.lb
RE at 600 in.lb
Bullet 1
Bullet 2
Bullet 3
Bullet 4


RE Bullet Load Readings
RE Torqued from 0 to 600 in.lbs,
after LE was torqued to 600 in.lbs
PHASE II
Relative Force, lbs.
Torque Sequence
RE at initial
RE at 100 in.lb
RE at 200 in.lb
RE at 300 in.lb
RE at 400 in.lb
RE at 500 in.lb
RE at 600 in.lb
Bullet 2
Bullet 3
Bullet 4
Bullet 1


LE Bullet Load Readings
LE Bolts torqued from 600 to 1080 in.lbs after LE bullets were adjusted
[after phase I, II and III)
PHASE IV
Relative Force, lbs.
Torque Sequence
LE at 720 in.lb
LE at 840 in.lb
LE at 960 in.lb
LE at 1080 in.lb
Bullet 1
Bullet 2
Bullet 3
Bullet 4


RE Bullet Load Readings
LE Bolts torqued from 600 to 1080 in.lbs after LE bullets were adjusted
[after phase I, II and III)
PHASE IV
Relative Force, lbs.
Torque Sequence
LE at 720 in.lb
LE at 840 in.lb
LE at 960 in.lb
LE at 1080 in.lb
Bullet 2
Bullet 3
Bullet 4
Bullet 1


LE Bullet Load Readings
RE Bolts torqued from 600 to 960 in.lbs after RE bullets were adjusted
RE Torqued from 0 to 600 in.lbs (phase II) & LE Torqued from 0 to 600 in.lbs (phase I)
PHASE III
Relative Force, lbs.
Torque Sequence
RE at 720 in.lb
RE at 840 in.lb
RE at 960 in.lb
Bullet 1
Bullet 2
Bullet 3
Bullet 4


RE Bullet Load Readings
RE Bolts torqued from 600 to 960 in.lbs after RE bullets were adjusted
RE Torqued from 0 to 600 in.lbs (phase II) & LE Torqued from 0 to 600 in.lbs (phase I)
PHASE III
Relative Force, lbs.
Torque Sequence
RE at 720 in.lb
RE at 840 in.lb
RE at 960 in.lb
Bullet 2
Bullet 3
Bullet 4
Bullet 1

8.0 Final Assembly

8.1 Quadrant Splices:

HGQ06 is the first magnet to be completed with double lead quadrant splices. All coils on HGQ06 have two leads per quadrant extending from the end, one being the usual coil lead and the other consisting of cable made with copper only strands, to be used as a stabilizer. All previous magnets had only single leads, except HGQ04, which was never completed.
Parts on the end which enclose the leads required some revisions to accept the double layers of cable. The new configuration of the double lead quadrant splices can be found in the assembly drawing MD-344925. The splice soldering tooling was also modified to accommodate four cables and the solder thickness.

The double lead design has one complication. When the splice is made, it is necessary that the two coil leads be soldered directly to each other, with the stabilizer (copper only) leads on the outside, as shown in Figure 8.1.1. This occurs naturally in two of the three quadrants to be spliced. In one of the splices, however, as the leads extend out of the magnet and are placed together, the stabilizer from one of the coils is sandwiched between the two coil leads. This problem was solved by cutting the stabilizer just before the splice and reversing its position, as shown in Figure 8.1.2.

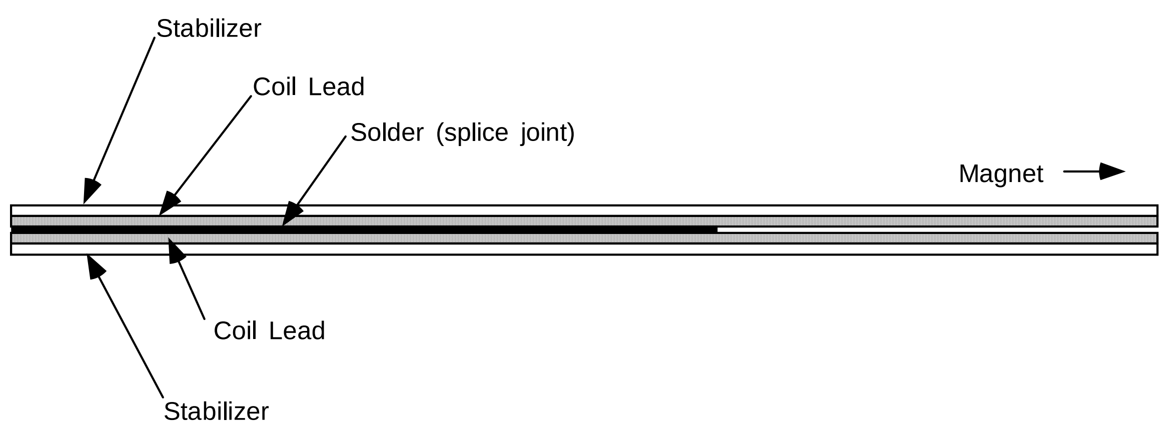


Fig. 8.1.1

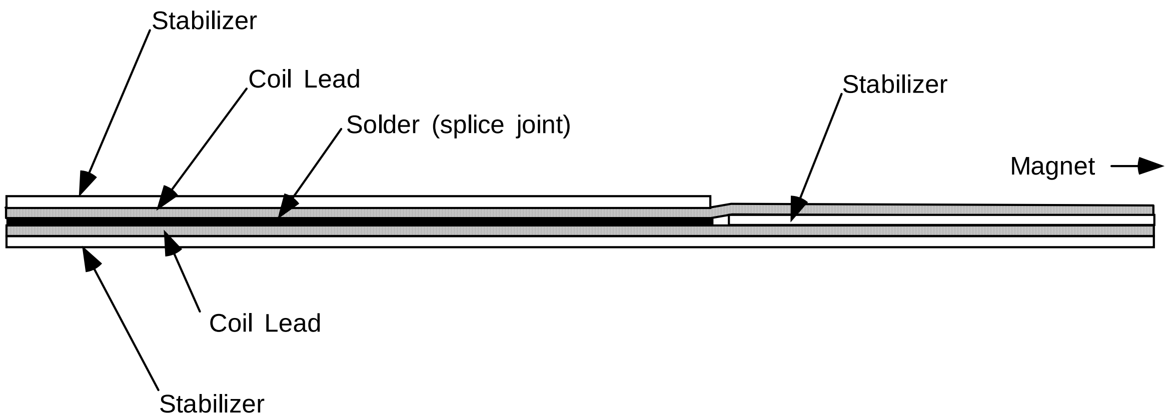


Fig. 8.1.2

A practice setup was completed on HGQ04, to make sure that the parts fit adequately and that the double lead cables could be shaped into the appropriate configuration. It was found during the test run on HGQ04, and again on the actual work on HGQ06, that the "regular" cables maintain their integrity much better than the copper-only cable. The copper-only stabilizer tends to come easily out of lay and not fit well into the parts cavity. Nevertheless, no significant problems were encountered during assembly.

After the splices were completed and soldered, a coil-to-coil short was detected, between quadrants 3 and 4. The problem occurred because the Kapton insulation around two of the leads was stripped during the cable bending, allowing two of the leads to make contact while going through the open area between the saddles and the quadrant splice parts. This may have occurred because the soft copper strands become unstable during forming, causing a potential for insulation breakdown. The quadrant splice area was disassembled and the leads were reinsulated, eliminating the short.

8.2 Skin Gauges: (From Joe Ozelis)

A total of 7 active strain gauges (Stk. # WK-09-250BG-350) are to be mounted in a longitudinal orientation along the length of the magnet. They are to be spaced approximately 30 cm apart, and arranged symmetrically with respect to the magnet longitudinal center. They are to be placed along the centerline of Quadrant 1, as done for previous LHC HGQ magnets. A single compensating gauge is to be placed in a longitudinal orientation, a few cm towards the return end from the active longitudinal gauge at the longitudinal center of the cold mass, co-linearly with the 7 active gauges.
Four additional active azimuthally oriented gauges are to be mounted at the magnet's longitudinal center, but placed 0, 30, 60, and 90 degrees away from the centerline of Quadrant 1. An additional compensating gauge, oriented longitudinally, is to be placed at the same azimuthal position as the 0-degree gauge described above, but shifted by a few cm longitudinally towards the return end.
In total, 15 strain gauges are to be placed on the shell, 11 active and 4 compensating. Nine are to be oriented so that their grids are parallel to the longitudinal axis of the cold mass, while 6 are to be oriented azimuthally.
See the diagram below:

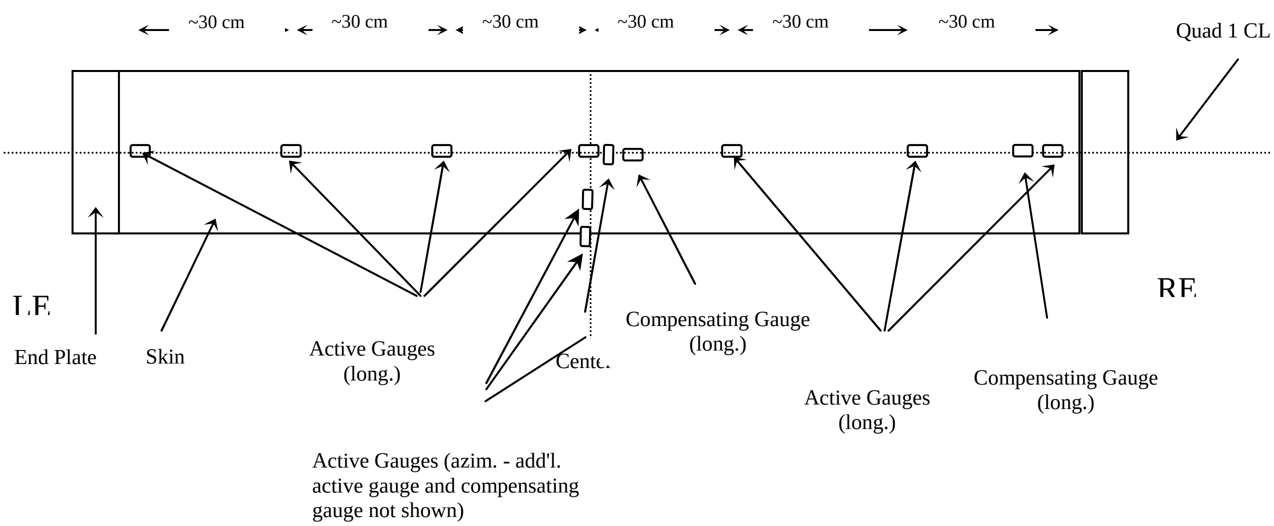


Fig. 8.2.1: Side View

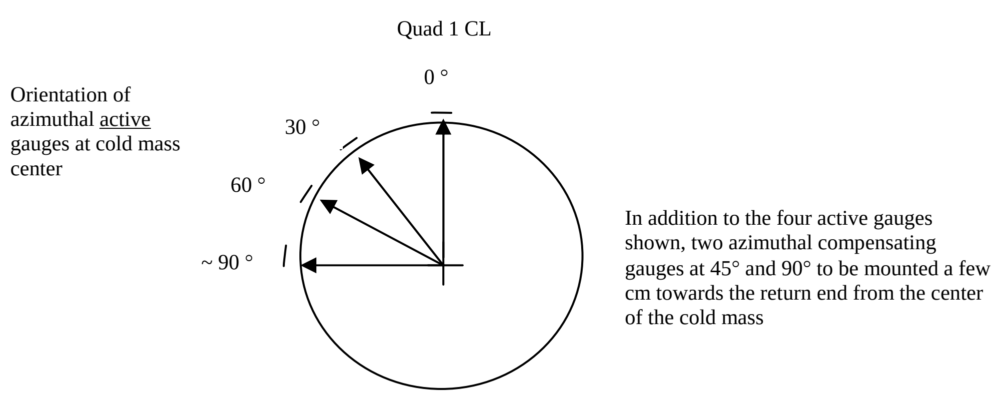


Fig. 8.2.2: End View

8.3 Final Electricals

HGQ-06 was hi-potted coil to ground, heater to ground and heater to coil at 1500 V. Leakage is required to be less than 0.5 μA at 1500 V. All the coils and the outer strip heaters passed the hi-pot testing except Quadrant # strip heater failed at 1.3 kV, by shorting to coil and to ground. No coil to ground short was detected.

The final electrical data collected before shipping to MTF:

	Resistance ohm	**Ls μ H**	**Q**
Q1 - inner	.0835	205.086	2.31
Q1 - outer	.1097	355.452	2.11
Q2 - inner	.0868	193.433	2.22
Q2 - outer	.1072	340.256	2.02
Q3 - inner	.0805	207.418	1.79
Q3 - outer	.1090	340.569	2.04
Q4 - inner	.0850	199.907	1.71
Q4 - outer	.1055	338.010	2.03
Q1 – Quadrant total	.1909	849.984	3.57
Q2 – Quadrant total	.1935	846.634	3.50
Q3 – Quadrant total	.1900	860.331	3.20
Q4 – Quadrant total	.1924	860.215	3.19
	Resistance ohm	**Ls MH**	**Q**
Magnet Total	.7681	4.784	4.32

Table 8.3.1: Magnet Resistance, L and Q measurements.

Heater	**Resistance ohm**
Q-1/2 - outer	3.696
Q-2/3 – outer	3.802
Q-3/4 – outer	3.682
Q-4/1 - outer	3.720

Table 8.3.2: Heater resistance measurements

The strip heater hi-pot test results are shown below: (From Rodger Bossert)

Outer Heaters to coil & ground		
Q1-Q2 outer heater to coil	.04uA @1500 V	all coils bussed together
Q2-Q3 outer heater to coil	.03uA @1500 V	all coils bussed together
Q3-Q4 outer heater to coil	.03uA @1500 V	all coils bussed together
Q4-Q1 outer heater to coil	short @1300 V	all coils bussed together
Q1-Q2 outer heater to ground	.03uA @1500 V	
Q2-Q3 outer heater to ground	.03uA @1500 V	
Q3-Q4 outer heater to ground	.03uA @1500 V	
Q4-Q1 outer heater to ground	short @1250 V	

Table 8.3.4 HGQ-06 Strip Heater Hi-Pot Test Result

One of the outer strip heaters on HGQ06 fails the hipot, both to coil and to ground, but the coil-to-ground hipot at 1500V is OK. This condition is almost identical to the situation in HGQ05, where one strip heater failed hipot both to coil and ground, but the coil-to-ground hipot was OK.

In both cases (HGQ05 and HGQ06), after the failure occurs, the heater can still be hipotted to the previous voltage before failure occurs again. In other words, the situation does not deteriorate.

The situation was almost identical, so here are the differences:

1) On HGQ05, the strip heater that failed was one of the inter layer heaters. All the outer layer heaters in HGQ05 were OK. In HGQ06, we have no inter layer heaters. It is one of the outer layer heaters, which is displaying this behavior.

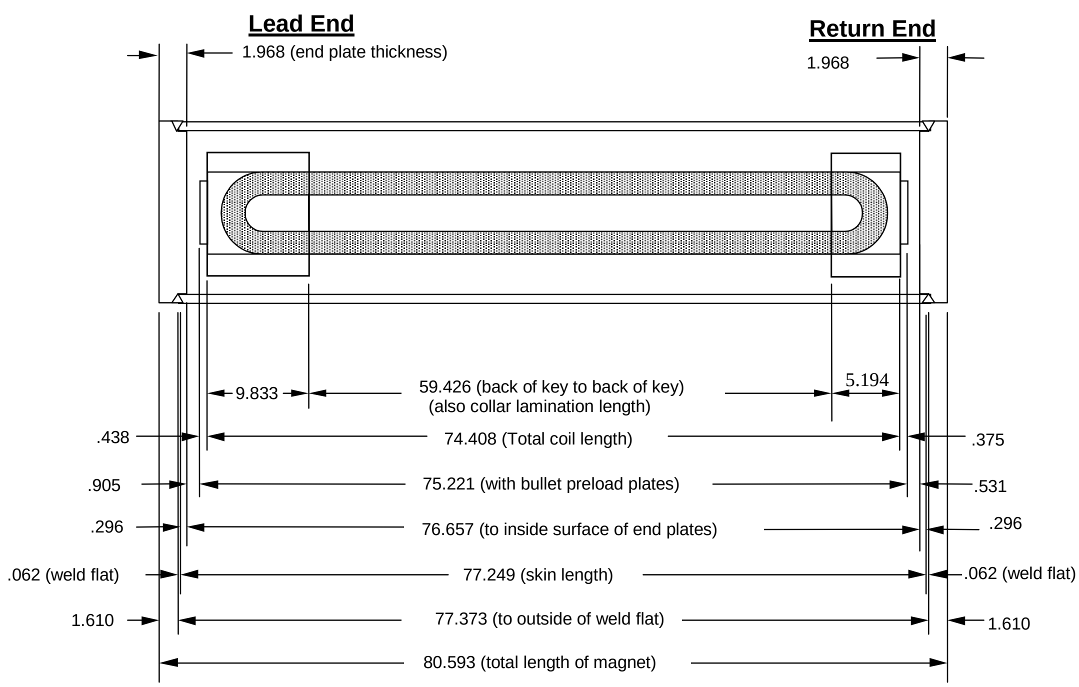
2) On HGQ06, the failures are at a slightly higher voltage than onHGQ05. The HGQ05 heater failed to both coil and ground at 800V, while the coil-to-ground passed at 1500V. On HGQ06, the “bad” heater fails to coil at 1300V and to ground at 1250V, while the coil-to-ground passes at 1500V.

3) On HGQ05, the heater to coil short became evident after installing the end clamps (before yoking). The heater to ground short became evident after the yoke was installed, but before installing the end plates and quadrant splices. On HGQ06, there were no hipot failures after yoking. The failures did not occur until the last hipot, just before shipping to MTF (but before ringing).

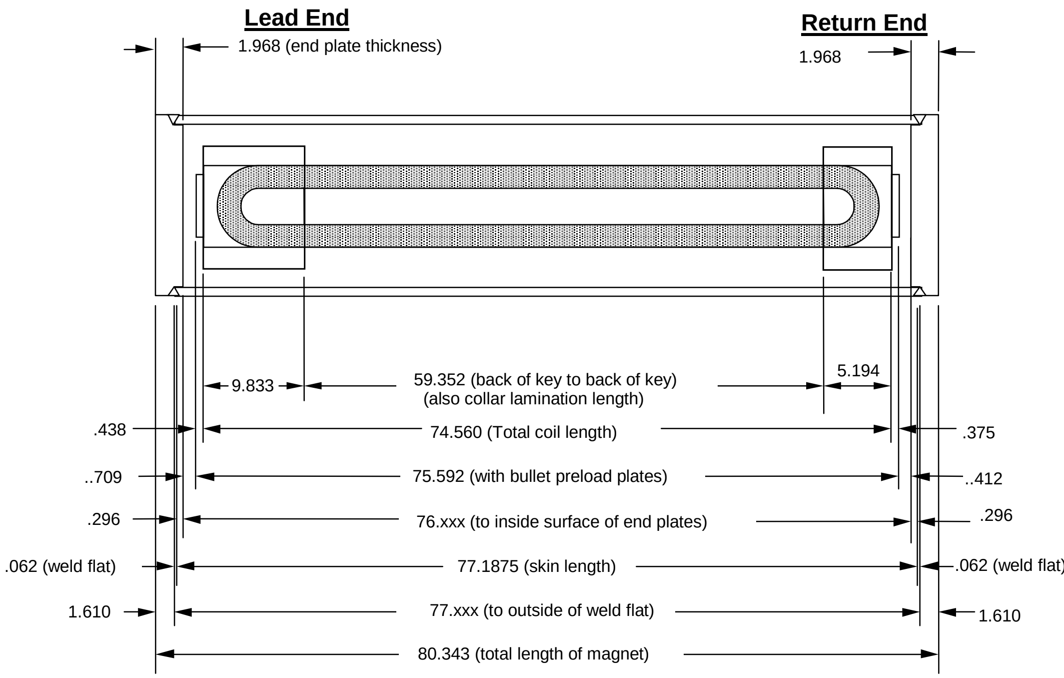
4) On HGQ06, an audible “click” can be heard when the failure occurs. This was not true on HGQ05.

Incidentally, we performed another standard hipot on HGQ05 in IB3 this week. The heater which previously failed still fails at about the same level, but one of the outer heaters now also fails to both coil and ground at 1400V and 1210V, respectively.
The coil-to-ground is still OK at 1500V.

8.4 Mechanical Measurements



These are the design dimensions for HGQ06



These are the measured dimensions for HGQ06